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NASA ELECTROSTATIC-THRUSTOR RESEARCH

AND INSTRUMENTATION

By

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INTRODUCTION

There exists today an interest in a great many different propulsion concepts for space flight application. Each concept has drawbacks and each offers a potential of being best suited for fulfilling the requirements of particular missions. They are frequently classed as chemical, nuclear, or electric with many subclassifications possible. Electrostatic propulsion is one subclassification of electric propulsion and the one with which this paper is concerned.

Discussed briefly herein are some of the basic principles, theories, and problem areas of electrostatic thrustors, and the effects that they have had on the evolution of thrustor concepts being investigated. Instrumentation and test facilities are areas that will also be discussed. Included is a reference list of more than 70 Lewis Research Center reports and papers that pertain to electrostatic propulsion.

BACKGROUND

The question of why electric propulsion is of interest is answered by requirements prescribed by mission analyses which show that to perform a given mission, a certain total impulse $\mathcal{I}$ is required. This total impulse can be expressed as

$$\mathcal{I} = Ft \tag{1}$$

where F is thrust and t is thrusting time. Now

$$F = \dot{m}_p v_{exh} \tag{2}$$

where $\dot{m}_p$ is propellant mass flow rate and v_{exh} is the exhaust velocity of the propellant relative to the spacecraft. Since $\dot{m}_p t$ is equal to the ejected mass of propellant m_p, these relations can be combined to yield

$$\mathcal{J} = m_p v_{exh} \tag{3}$$

The pros and cons of various propulsion schemes can be developed from these simplified expressions. Equation (1) shows, for example, that a given $\mathcal{J}$ can be obtained by application of a large thrust over a short period of time, or vice versa. Equation (2) shows that development of a large thrust requires a large $\dot{m}_p$ if v_{exh} is limited; equation (3) shows that this in turn requires a large propellant mass. Since this propellant mass is part of the vehicle total mass, it is evident that a limitation on the jet exhaust velocity leads to smaller payload fractions as the total impulse requirement increases. The payload fraction is the ratio of payload to gross vehicle weight. Thus, the stimulus for the interest in electric propulsion becomes apparent. By employing a scheme that ejects charged particles, a means of removing exhaust velocity limitations present in other systems is available. Less propellant mass is thereby required, and thus the payload fraction may be increased. There is a catch though, and, as it turns out, a very important one; that is, rather than a direct trade-off of propellant mass requirements, the additional mass of the powerplant for the generation of the electric power needed for electric propulsion must be considered. The result of this complication is shown in figure 1, which illustrates that a point is reached where the savings in propellant mass is offset by the added powerplant mass. Thus, for a given mission there exists an optimum specific impulse (proportional to exhaust velocity). This optimum value may not only be a variable that depends on additional mission restrictions (see e.g., refs. 3, 6, 35, and 68), but most important, from a practical viewpoint, can impose serious problems in terms of allowable thrustor mass, powerplant mass, power conversion equipment mass, propellant mass, and mission time. To be competitive with other systems from a time-of-mission viewpoint, the sum of these masses must be less. While this discussion has been an oversimplification of the problem, it should serve to set the stage in terms of what the overall goals are in electric propulsion research.

Some of the more important general requirements of the electric rocket thrustor are as follows:

(1) Operate at specific impulses dictated by mission analysis

(2) Have a reasonable size

(3) Have a low weight

(4) Be compatible with vehicle design and power generation system

(5) Operate reliably and continuously for months or years

(6) Convert electric power into thrust with near 100 percent efficiency

This imposing list (from ref. 37) is applicable to electric rocket thrustors in general, and since there are many concepts to choose from, it leads to the investigation of types that offer the best chance of accomplishing these goals. The choice is not clear cut. Three basic types of electric rockets being studied are shown in figure 2: electrostatic, electromagnetic, and electrothermal. All have practical as well as theoretical problems, discussions of which are plentiful in the literature. Reference 52 contains up-to-date discussions on most of the current concepts being studied. Of the three types shown in figure 2, the electrostatic thrustor has operated, in general, with the best overall efficiency.

ELECTROSTATIC THRUSTORS

Electrostatic Acceleration

The basic scheme of electrostatic acceleration is depicted in figure 3, where it can be seen that by application of a potential difference Φ_A over a distance L, ions are extracted from a source and ejected at a prescribed velocity. In this concept, electrons added to the exhaust beam at ground potential serve to maintain charge neutrality of the spacecraft and at the same time are prevented from returning to the thrustor by virtue of the negative potential applied to the accelerator electrode. The two equations (fig. 3) show that the thrust per unit area is proportional to the square of the field strength E_A, while the exhaust velocity (specific impulse) is porportional to the square root of the charge to mass ratio q/m and the net potential difference Φ_{net}.

These relations have an important influence on thrustor design. To obtain reasonable values of thrust per unit area, field strengths of the order of 10^6 v/m or greater are required. Field strengths are inversely proportional to accelerator spacing, which is a thrustor design parameter. There are obvious practical limitations with respect to attainable minimum spacings. Thermal environment and manufacturing tolerances at very small spacings become important particularly with respect to ion optics. Because of thrustor lifetime requirements, ion optics is an important problem area of electrostatic-thrustor research. Figure 4 shows that unfocused ions and/or ions formed by charge exchange may impinge on the accelerator electrode. These impinging ions can cause sputtering of the accelerator electrode. For lifetime requirements of several thousand hours, the allowable impingement must be of the order of 0.1 percent or less of the total ion beam.

The charge-exchange ions are a result of collisions between source ions and neutral propellant atoms present because of charging inefficiencies. Their elimination requires improved charging techniques. The unfocused source ions arise because of poor optics, and their elimination requires proper electrode design. Although the ion trajectory problem can be solved analytically for several "ideal" geometries (refs. 42 and 58), accounting for the exhaust aperture renders these solutions useful only as guide lines to good thrustor design. On the other hand, considerable progress has recently been made, both at Lewis and elsewhere, in developing suitable analog and numerical techniques for dealing with the "real" thrustor case, that is, methods that account for aperture effect (see e.g., refs. 51, 71, and 72). From a practical viewpoint, it is evident that increasing the accelerator spacing may greatly alleviate the problem. This approach may not be taken, however, without first examining the effect it may have on other operational parameters. These effects are shown in figure 5 (ref. 27). Recall that the thrust per unit area is proportional to the square of the field strength. Increased spacing means higher voltage if thrust is to be preserved. If singly charged particles are assumed, then a given value of specific impulse can be preserved by increasing the propellant molecular weight. Cesium and mercury are two commonly used propellants that require spacings of about 1 mm at a specific impulse of about 3000 sec. On the other hand, at the same specific impulse, accelerator spacing can be as much as 10 cm for 10,000 amu particles. Considerably higher voltages are required for these heavier particles.

Electrostatic Rocket Thrustor Efficiency

Equally important to good overall performance is the thrustor efficiency, which is defined as a product of the propellant-utilization efficiency and the power efficiency:

$$\eta = \eta_U \eta_P \tag{4}$$

The propellant-utilization efficiency is the ratio of charged to total propellant flow rates, or,

$$\eta_U = \frac{\dot{m}_+}{\dot{m}_{total}} \tag{5}$$

The power efficiency is defined conventionally as the ratio of power out (i.e., beam power) to total power in. It can be expressed in terms of thrust as

$$\eta_P = \frac{F^2}{2\dot{m}_+(P + \Sigma P_{loss})} \tag{6}$$

where

F thrust

$\dot{m}_+$ charged particle flow rate

P power invested in accelerating the charged particles

P_{loss} power losses

The power loss term consists of components that vary depending on the type of electrostatic thrustor being considered. Common to all types are power losses chargeable to ion impingement. Thus, ion impingement is important not only from a lifetime viewpoint, but also from efficiency considerations as well. For a more complete discussion of thrustor efficiency see references 37, 42, and 69.

With the fundamental goals outlined and the basic definitions in hand, the evolution in electrostatic-thrustor research at the Lewis Research Center may be easily traced.

Electrostatic Thrustor Types

Contact-ionization and electron-bombardment thrustors. - The two most common types of electrostatic thrustors are the contact-ionization thrustor and the electron-bomdbardment thrustor shown schematically in figure 6.

In the contact-ionization type, propellant vapor passes from a reservoir through a heated porous tungsten ionizer. It is ionized on the downstream surface of the porous tungsten. The ionizer is heated to enhance ionization and is also maintained at a high positive potential. The ions are then accelerated electrostatically to the desired exhaust velocity and electrons are injected to neutralize the ion beam.

In the electron-bombardment thrustor propellant vapor passes from a reservoir into an ionization chamber. Ionization is accomplished by collisions between the propellant vapor and electrons emitted from a heated filament. The outer wall of the chamber (anode) is maintained at a potential of about 40 v positive with respect to the filament, and an axial magnetic field of about 40 gauss is imposed on the chamber by the magnetic field coils. The magnetic field contains the energetic electrons emitted from the filament and enhances the electron - neutral-atom collision probability. A plasma is thus created within the chamber. Ions are extracted from the plasma through a screen grid and are accelerated to the desired exhaust velocity by application of a potential difference between the screen and accelerator. Electrons are emitted downstream of the accelerator to neutralize the ion beam.

The major power loss associated with the contact-ionization thrustor is the thermal-radiation loss from the porous tungsten ionizer. Major losses of the electron-bombardment thrustor include: power dissipated in the ion chamber discharge (called ionizer current in fig. 6); filament heating power; magnetic field power; and the neutral atom loss. The neutral atom loss is chargeable to the propellant-utilization efficiency and is also an important factor in the contact-ionization thrustor when operated at high current density. Research and development on both of these thrustors has led to prototypes that exhibit reasonably good performance at specific impulses greater than 5000 or 6000 sec (fig. 7). Current efforts are directed at improving efficiencies at specific impulses in the range of 2000 to 5000 sec, reducing thrustor weight and improving component life expectancy.

A cutaway of a flight test version of the Lewis electron-bombardment thrustor is shown in figure 8. The electron-bombardment thrustor has been reported on in detail in references 16, 19, 23, 36, 39, 50, 57, 63, 70, and 73. Although it is presently regarded as one of the better, if not the best, electrostatic thrustor, filament lifetime and propellant utilization are two developmental problems that remain to be optimized.

Several variations of the contact-ionization thrustor have been tested at Lewis (see e.g., refs. 9, 21, 24, 44, 56, and 62.) Extensive idealized theoretical analyses of various thrustor configurations have been made (refs. 42 and 69) and show that improvements in efficiency at lower values of specific impulse may be possible using certain design concepts. The theoretical performance of three design concepts are compared in figure 9 (from ref. 37). Designs compared are conventional paraxial flow, divergent flow, and circular flow. In preparing these curves it has been assumed that the accelerator electrodes act as perfect heat shields. Since the ionizer is completely shielded in the circular-flow concept, this assumption leads to a theoretical efficiency of 100 percent. Although the theoretical values shown will obviously not be attainable in practice, the curves are useful guides and show that because of the thermal-radiation loss, significant improvements in power efficiency at low values of specific impulse must be accomplished by means of "exotic" designs. Experimental models of the divergent-flow thrustor (see fig. 10) and a dual-beam circular-flow thrustor (see fig. 11) are presently being evaluated at Lewis.

Heavy-molecule thrustor. - As shown in figure 12, if the power losses expressed as electron-volts per beam ion are assumed constant in the electron-bombardment thrustor, it is theoretically possible to improve power efficiency by increasing the mass of the ion. It is appropriate then to investigate the performance of the electron-bombardment thrustor employing heavy-molecule propellants. Recall from figure 3 though that to preserve specific impulse the net accelerating voltage must be increased in direct proportion to the particle mass. Therefore, some modification of the thrustor is required. Various propellants are being investigated (see ref. 59). Performance is evaluated by determining an average charged particle mass from thrust and beam current measurements. As discussed in reference 59, preliminary results indicate that the high electron energies necessary to maintain the discharge in the ionization chamber may be the cause of considerable particle fragmentation. And it appears that additional modifications in thrustor geometry and/or the ionization process will be required to achieve the anticipated improvements in performance.

Colloidal-particle thrustor. - The variation of specific impulse with propellant mass in atomic mass units is shown in figure 13 for various values of accelerating voltage. The shaded region covers a range of specific impulse of most interest for missions such as a manned Mars round trip. As previously discussed, improvements in efficiency are theoretically possible if the charged particle mass is increased, however, increased accelerating voltages are required. Plots such as figure 13 are useful, therefore, in establishing upper bounds of feasibility within the range of specific impulse of interest. If, for example, power-generation equipment capable of producing voltages of the order of 500,000 to 1,000,000 v becomes available, singly charged particles of from 10^4 to 10^5 amu may be of interest. The colloidal-particle thrustor affords a means of accomplishing charged particles in this mass range. Several methods of colloidal-particle production have been proposed. One concept, which is under investigation at the Lewis Research Center, is shown in figure 14. In this concept, propellant vapor passes through a supersonic nozzle and undergoes a condensation shock in the region downstream of the throat. Particles formed by homogeneous nucleation pass through a growth region and enter a charging region. There they are charged by electron attachment and subsequently are accelerated to the proper exhaust velocity. As shown in figure 14, the exhaust beam consists of negatively charged particles, and beam neutralization requires the injection of positively charged particles. Figures 15 and 16 show two Lewis experimental colloidal-particle thrustors. Formation of particles in both thrustors is accomplished as described. Particle charging is achieved by electron attachment (negative particles) in the former and by electron bombardment (positive particles) in the latter.

For the colloidal-particle thrustor to be useful it must be capable of the efficient production of particles of uniform charge to mass ratio. It is toward this goal that the primary objectives of the Lewis research program is directed. Results to date from the "negative-particle" colloidal thrustor using mercurous chloride and aluminum chloride propellants have been very encouraging (see refs. 43 and 66). Charge to mass ratios reported in references 43 and 66 were, however, calculated from indirect measurements. In this respect, lack of adequate instrumentation poses the most difficult problem in evaluating thrustor performance. Though there are many challenging factors affecting thrustor performance that remain to be evaluated, the potential advantages of this type of thrustor are many.

Figure 17 shows the variation in thrustor efficiency with specific impulse for the various thrustor concepts. The three lower curves are based on existing data, while the upper curves are theoretical. The successively higher curves, starting with the existing contact-ionization curve, to a great extent trace the evolution of the Lewis electrostatic-thrustor research program to its present status. The high theoretical efficiency of the colloidal-particle thrustor and the reasonable accelerator length requirements that arise as a result of utilizing charged particles of larger mass are features that make this type of thrustor most attractive. The required high voltages focus attention on the power-generation and power-conversion requirements.

POWER GENERATION

A survey paper on electrostatic-thrustor research, even one restricted to the work of a single organization as this one is, cannot ignore the tremendous problem facing electric propulsion in the area of power generation. It was shown in figure 1 that the merits of electric propulsion for space flight are closely tied to the mass of the powerplant. In terms of a mission-analysis parameter, powerplant mass is usually related to the power generation ability and expressed as kilograms or pounds per kilowatt of electrical power. Figure 18 (from ref. 75) shows the effect of powerplant specific mass on trip time and payload fraction for a possible round-trip manned Mars mission. Details of the assumptions and calculations used for this figure are given in reference 75. For our purposes it is sufficient to note that powerplant specific masses shown in the figure are 10 kg/kw or less. These values are well below those attainable with any existing equipment today. Because of the trip time, the mission described by the curves of figure 18 is regarded as a difficult one for electric propulsion. It does, however, exemplify the very important need for reliable lightweight power-generation equipment. Some of the power generation systems presently being considered for space flight application along with estimates of typical theoretical specific weight are given as follows:

Power-generation system	Theoretical specific weight, (lb/kw) for power level > 100 kw
1. Solar cells (thin film)	20
2. Nuclear turboelectric	6
3. Nuclear thermionic	4
4. Nuclear MHD	4
5. Solar thermoelectrostatic	1
6. Radioisotope electrostatic	1

The low-power-level solar cells in present use have much greater specific weights, as do low-power-level nuclear turboelectric power-plants currently being developed. For the most part, the tabulated values are based on work done thus far in the form of feasibility studies and are likely to be optimistic. The radioisotope electrostatic generator has, for example, been subject to extensive theoretical analyses (refs. 41, 53, 64, and 65), and although assumptions of the analyses seem reasonable, there are many system unknowns. Questions regarding radio-isotope availability and launch pad hazards that may easily be raised do not appear unsolvable. The low theoretical specific weights seem to justify an experimental investigation for evaluation of the more important unknowns and assumptions of the analyses. A mock-up of a manned electric spacecraft using a radioisotope generator is shown in figure 19.

INSTRUMENTATION

The experimental evaluation of an electrostatic thrustor is a task complicated by many factors. Some problems are common to all thrustors and relate to vacuum-facility requirements (i.e., pressure levels required), the presence of vacuum-facility walls, and the fact that the thrustors all employ electrostatic acceleration of either positively charged or negatively charged propellants. Other problems are associated with the particular thrustor concept being evaluated. The effects of these complications as related to instrumentation are many. Some have been solved; many have not.

A discussion of all of them is beyond the scope of this paper. From the list of thrustor requirements set down earlier, it is evident that the experimental investigator is primarily concerned with utilizing those instruments that will enable him to determine accurately the efficiency of a given experimental thrustor and at the same time, anomalous as it may seem, identify the inefficiencies. For example, while conventional current and voltage reading meters may be used (and frequently are used) to determine the exhaust beam total power, metered values yield no information with regard to thrust losses that may be present due to skewness of some fraction of the exhaust beam.

Instruments that have been used in the electrostatic-thrustor research program at the Lewis Research Center are given in the following table. Quantities measured are given and, when applicable, references are also listed where additional detail may be found

Instrument	Measurement	References
(1) Conventional meters	Current, voltage	--------
(2) Conventional thermocouples	Component temperatures	--------
(3) Optical pyrometers	Component temperatures	--------
(4) Can calorimeter	Beam power density	22
(5) Hot-wire calorimeter	Beam power density	17,18,22
(6) Molybdenum-tipped probe	Beam current density	39
(7) Thin film collector and electron microscope	Particle mass	43
(8) Can microbalance	Thrust	66
(9) Cone-thrust target	Thrust	--
(10) Mass spectrometer (various types)	Beam particle charge to mass ratios	48
(11) Emissive probe	Beam potential	55,73
(12) Total radiation pyrometer	Heat flux	28
(13) Plasma potential probe	Beam potentials and field strengths	30
(14) Plasma oscillation probe	Beam ion-plasma waves	30
(15) Magnetic ammeter	Net beam current	77
(16) Flow meter	Gas flow through porous tungsten	28
(17) Neutral atom probes	Neutral atom distribution	70,78

Only a few of the several instruments listed are described herein.

Items (1) to (3) are familiar and require no further description. However, as discussed in reference 22, special precautions in the use of current meters may be necessary to ensure meaningful data. Secondary electrons from facility walls may arrive at thrustor components and complicate meter readings. Internal to the thrustor itself, accelerator drain currents may consist of several components (e.g., ion impingement, secondary electrons, and thermionic emission) which cannot be separately identified. Identification of these "internal currents" is, in fact, one of the major instrumentation problems of experimental electrostatic-thrustor research. (See refs. 23, 39, 62, 70, and 76.)

Beam Power Density Measurement

The calorimeters (items (4) and (5)) are small probe-type instruments that when used individually yield information about local beam power density. By using multiple arrays, however, it is possible to construct "contour-maps" from which the total beam power may be determined.

Can calorimeter. - A can calorimeter is shown in figure 20. Beam power densities on the copper plate are determined by measuring the heat flow in the inner shell. The thermal calibration constant (degrees per watt) can readily be determined from measured values of electrical resistance and known physical properties of the copper inner shell. The unit has the advantage of being a simply constructed direct reading device. Radiant heat flux losses from the copper plate place an upper limit on their range of applicability, and response times are of the order of minutes. As with all probe devices used in charged particle beams, it is subject to uncertainties due to surface interactions with the impinging beam.

Hot-wire calorimeter. - The hot-wire calorimeter shown in figure 21 is an excellent instrument for detailed probing of charged particle beams because of its very small sensing unit. The sensing unit consists of a fine electrically heated wire (0.001-cm diam. by 0.50 cm are typical dimensions) that responds to charged-particle bombardment with a voltage output proportional to temperature (resistance) change. Response times are very good, so that with a rake consisting of several units, surveys of a beam can be completed in less than 0.5 min. A typical contour map constructed from a survey of an ion beam is shown in figure 22. Accurately determining hot-wire calorimeter sensitivity constants is a somewhat arduous task and requires very careful measurement of the physical dimensions of the wire. The contour maps are informative, but processing raw data and construction requires at least a half day per map.

Beam Current Density Measurement

Molybdenum-tipped (moly button) probe. - A schematic drawing of the moly-button probe is shown in figure 23. Similar to the calorimeters, several moly-button probes may be used simultaneously to obtain data for construction of contour maps of the local beam current densities. Integration of the contour map then yields values of total beam current that may be compared with metered values. The tips are typically 3/16-in. in diameter by 0.05 in. Molybdenum is used because of its low secondary electron yield coefficient. Biasing the probe slightly negative (see fig. 23) enhances emission of secondaries but is found to be necessary to discourage collection of electrons from external sources. It is estimated in reference 39 that the maximum error due to secondary electrons is less than 10 percent for 4000 ev heavy ions. While lacking the sophistication of an instrument such as the hot-wire calorimeter, it is an extremely useful device. Ion optics (i.e., focusing effects within the thrustor), for example, are readily investigated with moly-button probes.

Thrust Measurement

Ion beams from contact ionization thrustors with cesium as a propellant are usually considered to consist of singly charged atoms. Mercury ion beams have been found to contain singly, doubly, and triply charged atoms (ref. 48). However, under most operating conditions the latter two species make up a relatively small fraction of the total beam. Because beams from heavy-molecule and colloidal-particle thrustors may consist of a large range of particle distribution in both mass and charge, more specialized instrumentation is required to investigate and evaluate thrustor performance. While thrust targets that collect the total thrustor exhaust beam are not the answer to this problem, they can be used in connection with other instrumentation to determine average values. Of course, thrust in itself is an important performance parameter.

Two types of thrust targets have been used with success at Lewis.

Cahn microbalance. - A Cahn microbalance is being used to measure thrust of the order of 10^{-5} newtons from a colloidal-particle thrustor that uses mercurous chloride as a propellant. Once calibrated, the microbalance is a direct-reading device. In an experimental setup, shown schematically in figure 24 (from ref. 66), the microbalance also served as a beam current collector to check conventional meter current values. The metered beam current and accelerating voltage were used together with the thrust measurement to determine an average particle mass of 1.2×10^{6} amu. This value compared well with a value of 1.7×10^{6} amu that was determined by an entirely different method (ref. 43). In the setup of reference 43, particles were collected on a liquid-nitrogen-cooled thin-film collector that was exposed to the colloidal-particle beam for a very short time. Photomicrographs of the collector were taken with an electron microscope. Particle-size distribution was determined from the micrographs and an average particle mass was then calculated.

Cone thrust target. - The cone-type thrust target shown in figure 25 is being used in heavy-molecule thrustor research. Thrust levels measured are of the order of 10^{-4} newtons. With the cone-type target, thrust values must be determined from measured deflections. Deflections are measured with a cathetometer which is focused through a viewing port in the facility on the crosshairs shown in figure 25. Calibration is accomplished by measuring deflections when known masses are suspended by a pulley arrangement from the cone tip. Typical calibration constants are about 10^{-5} newtons per millimeter deflection.

Charge to Mass Ratio Measurement

Although useful for evaluating overall thrustor performance, thrust targets are not suitable for evaluation of losses in terms of charge and/or mass distribution. Investigation of this requires more complex equipment such as mass spectrometers. While mass spectrometer technology is not new, the design of spectrometers suitable for use in electrostatic thrustor work imposes severe requirements that are very difficult to satisfy. This is particularly true when applied to colloidal thrustor work.

Colloidal thrustor experimental research is in its early stages, and much is not yet known about particle formation and/or particle charging processes. It is reasonable to anticipate the possibility of wide charge to mass distributions in the exhaust beams, which also are high velocity beams. Thus, the need exists for a small, lightweight, mobile instrument capable of accepting high velocity particles and also having a high resolution over a mass range of from 10^2 to 10^5 amu (assuming singly charged particles).

Permanent magnet mass spectrometer. - The magnetic spectrometer described in reference 48 worked quite well when used to analyze a mercury ion beam from an electron-bombardment thrustor. However, the size and entrance velocity requirements of the permanent magnet mass spectrometer limits the utility of this instrument for electrostatic thrustor research. The quadrupole mass spectrometer appears to be more suitable.

Quadrupole mass spectrometer. - A photograph of a quadrupole mass spectrometer which has been designed and built for use in colloidal propulsion research at Lewis is shown in figure 26. It is presently undergoing extensive calibration tests. In operation, particles enter the quadrupole through a small opening in the lower end (fig. 26). By superposition of an r-f voltage (of a particular frequency) on a d-c voltage applied to opposing pairs of rods, particles of a particular charge to mass ratio will be "trapped" in the region between the rods and caused to follow trajectories such that they will arrive at a current-sensing collector. The collector is located at the upper end of the rods shown in figure 26. The length of the rods is a design parameter relating the frequency of the r-f voltage, resolution, charge to mass ratio, and particle entrance velocity. The field radius (distance from centerline to rods) and frequency determine the power requirements. The ratio of the rod radius to the field radius is chosen so as to approximate the required theoretical field and achieve a high transmission. Consequently, tolerances (mechanical and electrical) must be held quite close.

Complete details of the operation of the quadrupole are beyond the scope of this paper. The reader will find that an article entitled "The Electric Mass Filter as a Mass Spectrometer and Isotope Separator" by W. Paul, et al., Zeitschrift für Physik, Ed. 152, S. 143-182 (1958) an excellent reference that includes both a theoretical analysis and experimental evaluation of a high resolution quadrupole mass spectrometer. An English translation AEC-TR-3484, Oct. 23, 1958, by Dr. John F. Burns is also available.

In the tests thus far at Lewis, problems have been encountered in power supply regulation and electrical shielding. The collector is extremely sensitive to effects of the high frequency field. Thus, while it is a very sophisticated instrument, its utility to colloidal thrustor research makes it worthy of considerable developmental effort.

Neutral Atom Measurement

In the cesium contact-ionization thrustor, which employes a porous tungsten ionizer, measurement of neutral propellant flow rate is often accomplished indirectly. Room temperature nitrogen gas is used for calibrating the flow through the ionizer, and suitable corrections for atomic weight are applied to obtain a flow rate for cesium (see ref. 62). The electron-bombardment and heavy-molecule thrustors employ orifices to control flow, and flow rates are determined by direct calibration of the orifice. In the colloidal-particle thrustor, flow in the nozzle is fully developed and flow rates are calculable. Thus, propellant-utilization efficiencies can be determined for all of these thrustors. However, none of these measuring or calculation techniques cast any light on the fate of the propellant atoms or particles that fail to become ionized. A knowledge of the efflux distributions of these "neutrals" would be of great value to aid in improving thrustor design and performance. What is required to obtain this information is a probe-type instrument capable of probing the thrustor exhaust beam and identifying the "neutrals." This is an exceedingly difficult problem in instrumentation not only because of the complex local environment (ions, electrons, neutrals) but also because of the properties of the various propellants.

Alkali metal propellants such as cesium are amenable to probes that employ principles of contact ionization. A probe of this type has been developed at Lewis and has been used for the study of neutral cesium efflux patterns from 1/8-in.-diameter cylindrical tubes (ref. 78). Neutral cesium atoms pass through a small opening in the outer cylindrical shell of the probe. The atoms contact a heated tungsten ribbon located on the probe axis. The ribbon is biased positive with respect to the outer shell and cesium atoms created on the ribbon are collected on the shell. Minimum currents of about 10^{-9} amp are detectable with this instrument.

A hot cathode ionization gage (Bayard-Alpert type) mounted just downstream of the accelerator of an electron-bombardment thrustor has been used to obtain rough estimates of neutral mercury efflux (ref. 70). Uncertainties in gage calibration for mercury vapor along with side effects due to the ion beam indicate that a great deal of development would be required for wide use of this method of detection. In general, the state of the art in the development of instruments for detection of nonalkali neutral propellant efflux patterns is very lacking.

Other Instrumentation

Of the remaining instruments listed, many are special purpose in that they were developed and used for research in particular problems and, in general, are not used in thrustor performance investigations. Although discussion is beyond the scope of this paper, it is appropriate also to point out that a considerable amount of valuable instrumentation work is being done by other organizations. Unique cesium neutral atom probes, calorimeters, thrust stands, and plasma probes are only a few of the areas in which much work has been done. Instruments for beam neutralization studies, described in part of references 55 and 73, are examples of excellent advanced measurement techniques necessary to fundamental investigations of plasma properties in thrustors. As stated at the beginning of this section, there unfortunately are many instrument problems still remaining in electrostatic-thrustor research.

FACILITIES

High-vacuum facilities for testing electrostatic thrustors, in addition to being capable of being evacuated to pressures of the order of 10^{-7} torr, must be capable of maintaining background pressures on this order during tests. Because the thrustor exhaust beam imposes a severe load on facility pumps at these pressure levels, special design features are necessary that are not required in ordinary space environment facilities. Condensers that provide large areas of surfaces cooled to near liquid nitrogen temperatures are used as a means of maintaining the desired levels of pressure. Most of the propellants used in electrostatic thrustors are condensable at liquid nitrogen temperatures, that is, their equilibrium vapor pressures are orders of magnitude below 10^{-7} torr. A theory of high vacuum condenser design is given in reference 2 and results of an experimental evaluation are reported in references 33 and 49.

There are several major high-vacuum facilities at the Lewis Research Center used for the purpose of electrostatic and plasma thrustor research. The main chambers of these facilities are cylindrical and range in size from about 3.5 ft in diameter by 7 ft long to 25 ft in diameter by 70 ft long. They have been described in detail in references 4, 14, and 25. They are similar in design and are evacuated by from one to twenty 32-in. cold-trapped oil-diffusion pumps supported by suitable backup pumps. All chambers are provided with liquid-nitrogen-cooled condensers. The newest and largest facility is shown schematically in figure 27 (from ref. 25). The thrustor compartment is about 10 ft in diameter by 10 ft long and can be sealed off from the main chamber by a 10 ft diameter isolation valve. This allows thrustor modifications to be performed while the main chamber remains evacuated. The condenser in the main chamber is cooled by a forced-feed liquid-nitrogen system. Liquid nitrogen is circulated through stainless-steel tubes located along the periphery of the main chamber. Copper honeycomb units about 3 in. by 3 in. by 6 in. deep are securely fastened to the tubing and serve both to protect the tubing from direct impingement of high-energy thrustor exhaust beams and to provide the necessary surface area for condensation of the beam. The cone-shaped water-cooled target at the far end of the chamber is designed to remove energy from the beam and to direct reflected particles toward the outer walls. Two photographic views of the facility are shown in figures 28 and 29. The facility was placed in operation early this year, and during its initial check-out tests maintained pressures of about 10^{-7} torr. In subsequent runs using the liquid-nitrogen-cooled condenser, no-load pressures of 10^{-8} to 10^{-9} torr were recorded. Research experiments not yet reported on beam diagnostics and on the testing of modular arrays of three electron-bombardment thrustors have been conducted in the facility. Although this facility is comparatively large, much larger facilities may be needed for long duration testing of full-scale electric propulsion systems.

CONCLUDING REMARKS

To apprise the reader of the present status of the electrostatic-propulsion research effort at the Lewis Research Center, a very general and broad approach was adopted herein. Several aspects of the program and related programs have been mentioned to the extent that it was necessary to point out major overall goals and problem areas. Related areas not covered include power-conditioning equipment and controls problems.

From examination of basic equations of mission analysis it was shown that electric propulsion is attractive as a means of space flight because of reduced propellant mass requirements as compared with other systems. To make the comparison complete, however, the mass of the power-plant required for the electric rocket must also be taken into account. It was pointed out that present power-generation equipment is far too heavy for electric propulsion and a need exists for the development of lightweight equipment with high power capabilities.

In tracing the evolution of the electrostatic-thrustor research program it was noted that existing cesium contact-ionization and mercury electron-bombardment thrustors both have power loss factors that make them inefficient at specific impulses below about 5000 sec. It was shown that theoretically, the heavy-molecule and colloidal-particle thrustor may have better efficiencies in the 2000- to 5000-sec range of specific impulse. Further, although the larger molecular weights of the charged particles in these thrustors impose a requirement of greater accelerating voltages to preserve specific impulse, thrust could be preserved with larger electrode spacings. Thus, thrustor design and fabrication may be made somewhat easier, and ion optics in the thrustor may also be improved.

A review of instrumentation that has been developed for experimental thrustor research showed that many instruments have been developed that are suitable for overall performance evaluation. Instrumentation for isolating and identifying thrustor losses is being developed, however, many types are still needed. No adequate instrumentation exists for monitoring neutral propellant losses from thrustors employing nonalkali propellants.

Existing electrostatic-thrustor research facilities are adequate for present needs, but much larger facilities may be required in the future for full-scale system tests.

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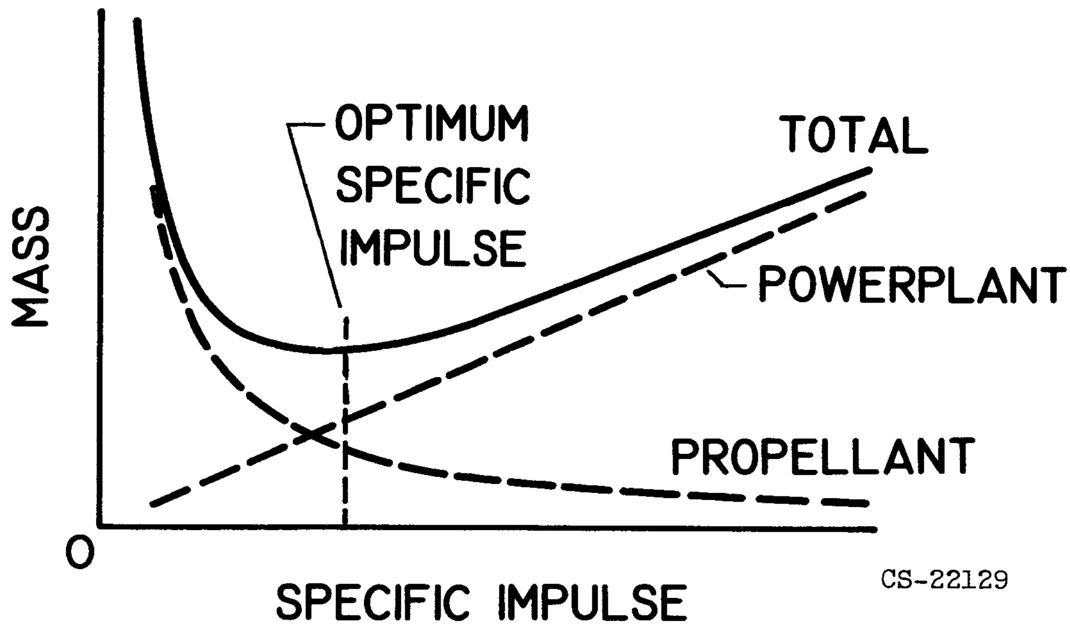

Fig. 1. - Variation of mass with specific impulse.

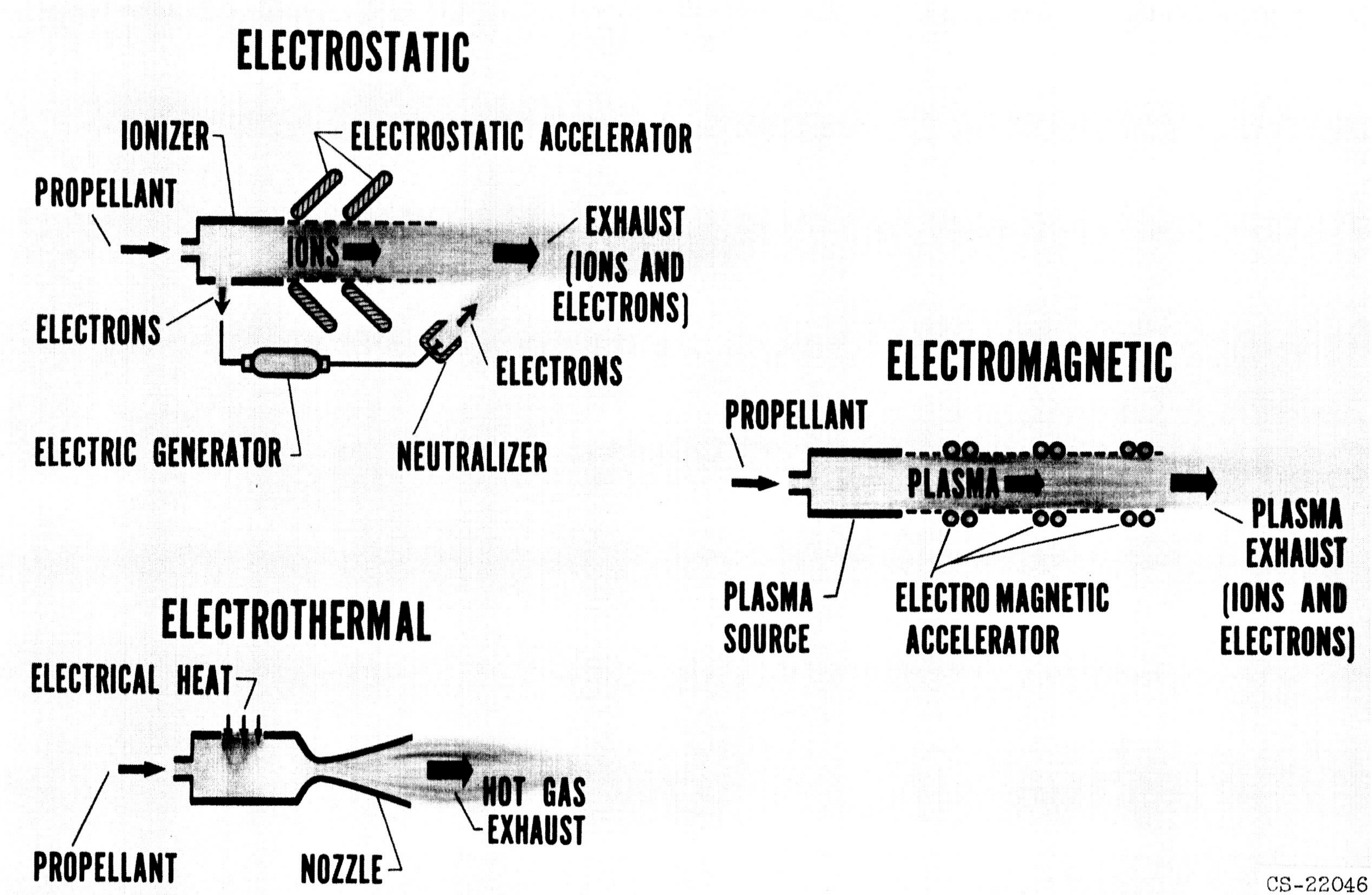

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Fig. 2. - General classification of electric rocket thrustors.

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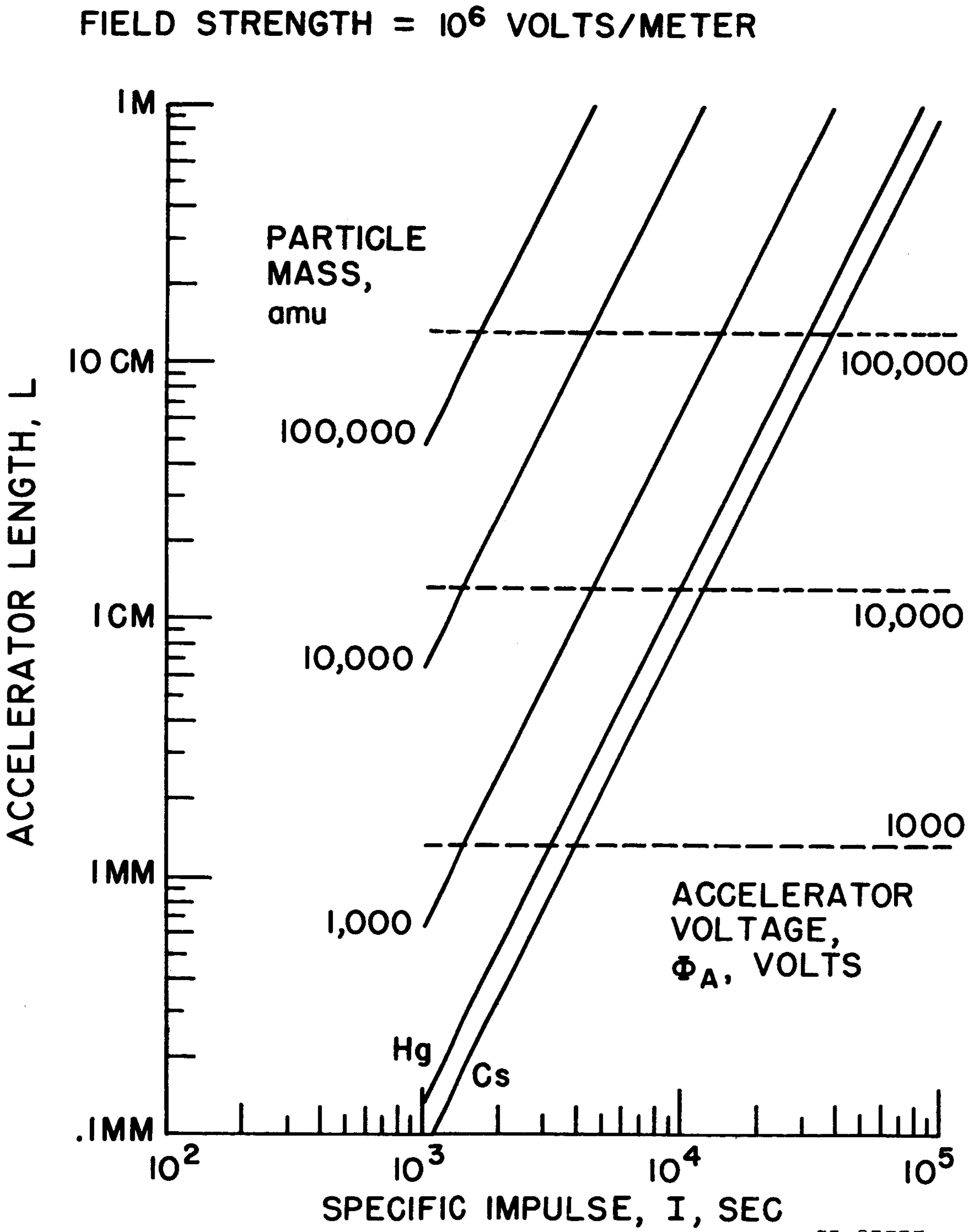

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Fig. 5. - Accelerator length.

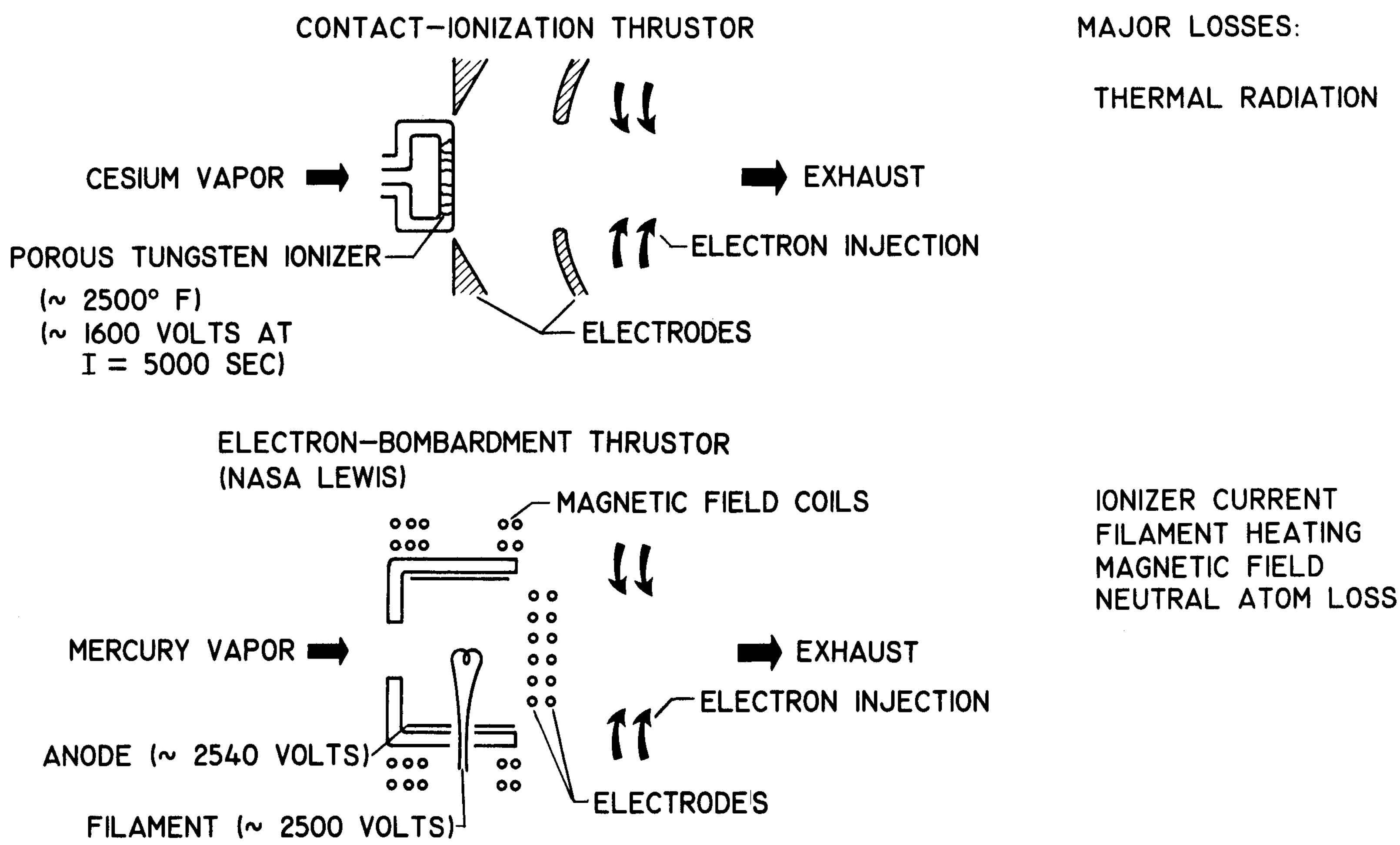

Fig. 6. - Electrostatic thrustor types.

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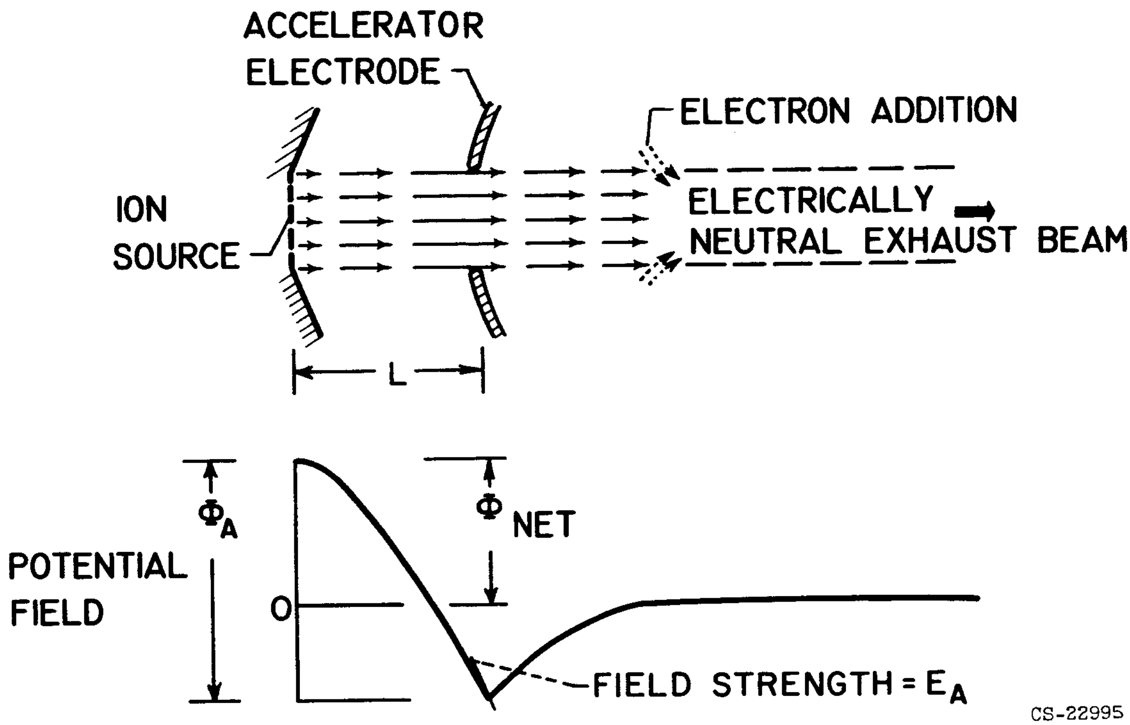

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$$\text{EXHAUST VELOCITY} = v = \sqrt{2\,\frac{q}{m}\,\Phi_{NET}}$$

$$\frac{\text{THRUST}}{\text{EXHAUST AREA}} = 4.43 \times 10^{-12}\, E_A^2 \left(\frac{\Phi_{NET}}{\Phi_A}\right)^{1/2}$$

Fig. 3. - Electrostatic acceleration of ions or charged particles.

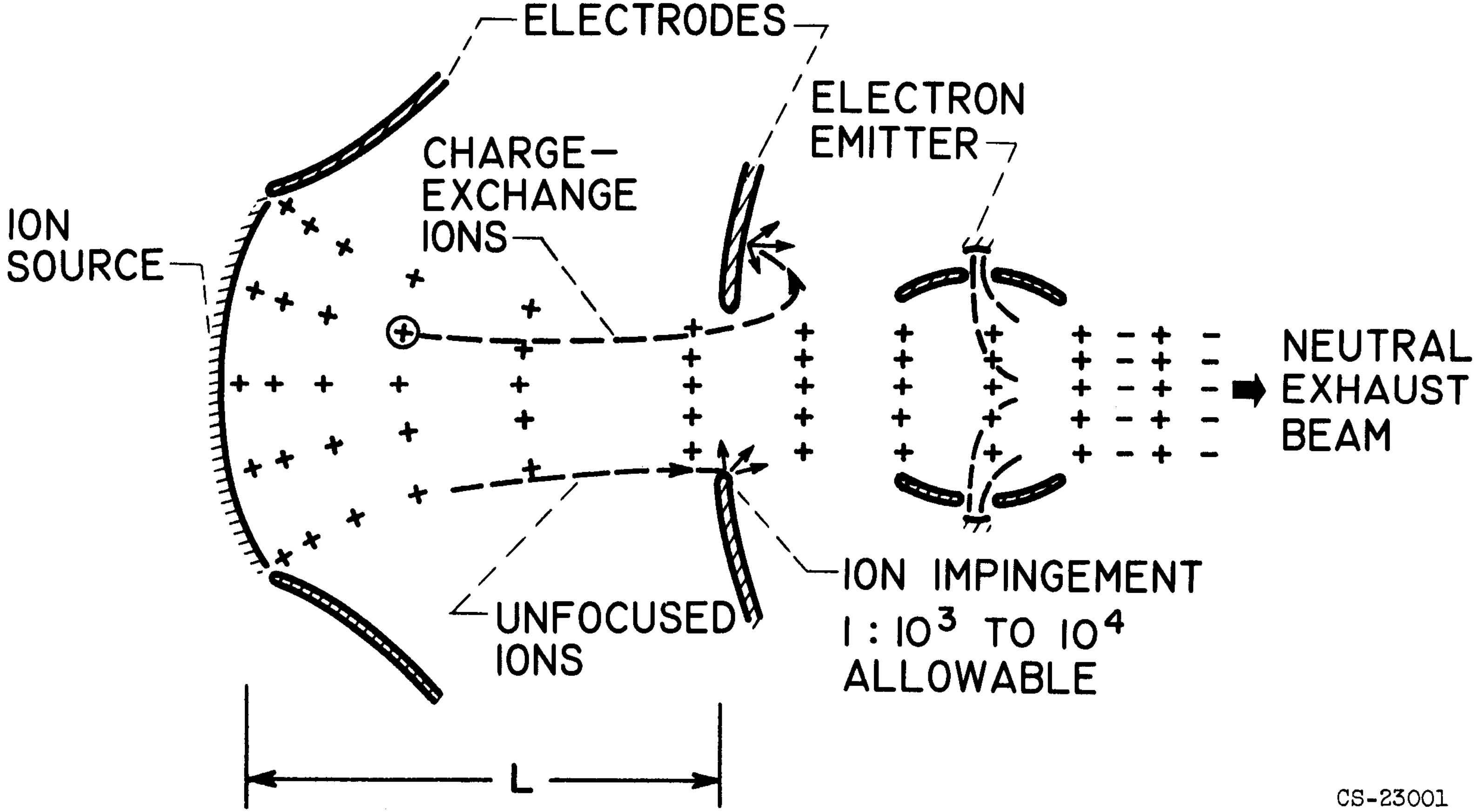

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Fig. 4. - Ion impingement and electrode sputtering in electrostatic thrustors.

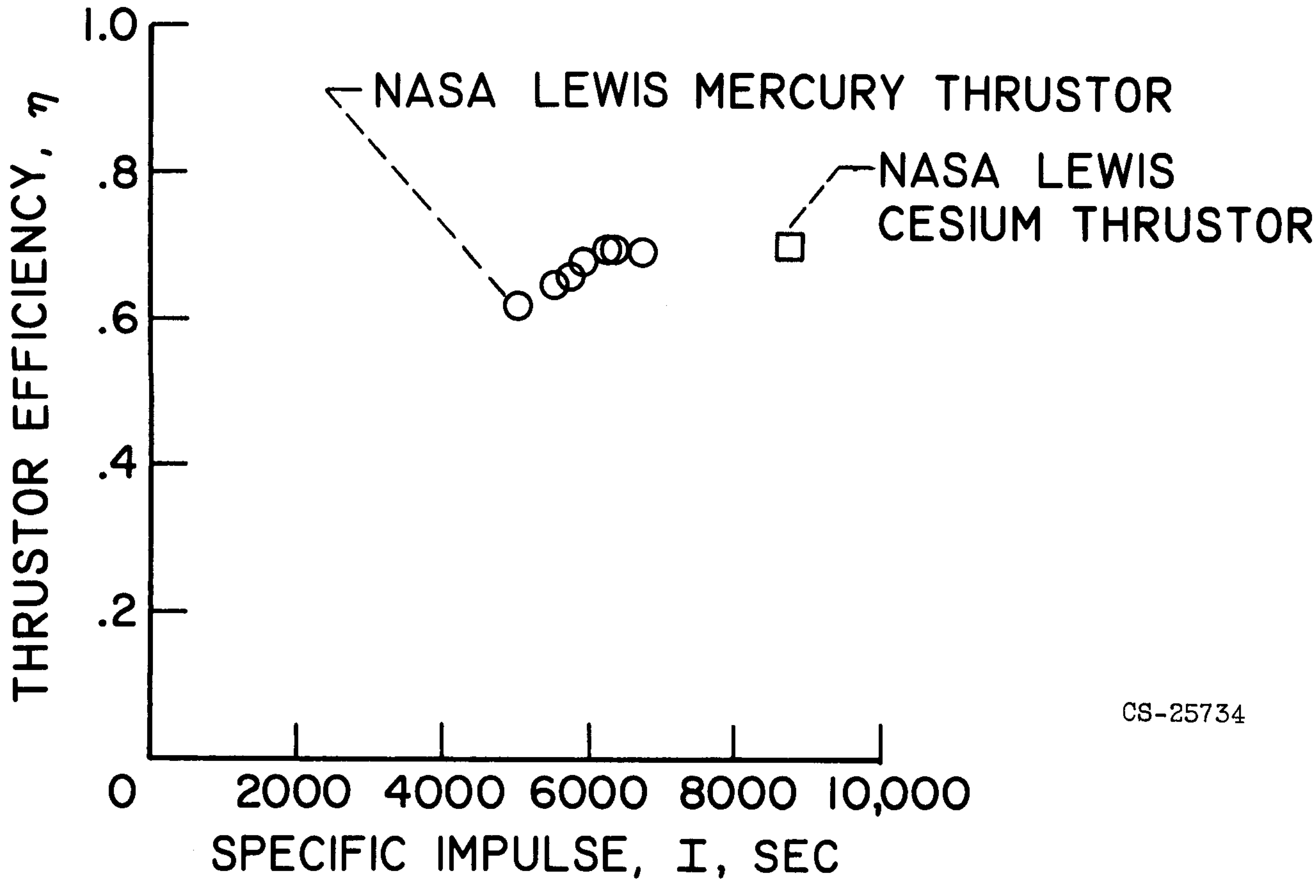

Fig. 7. - Experimental thrustor efficiencies.

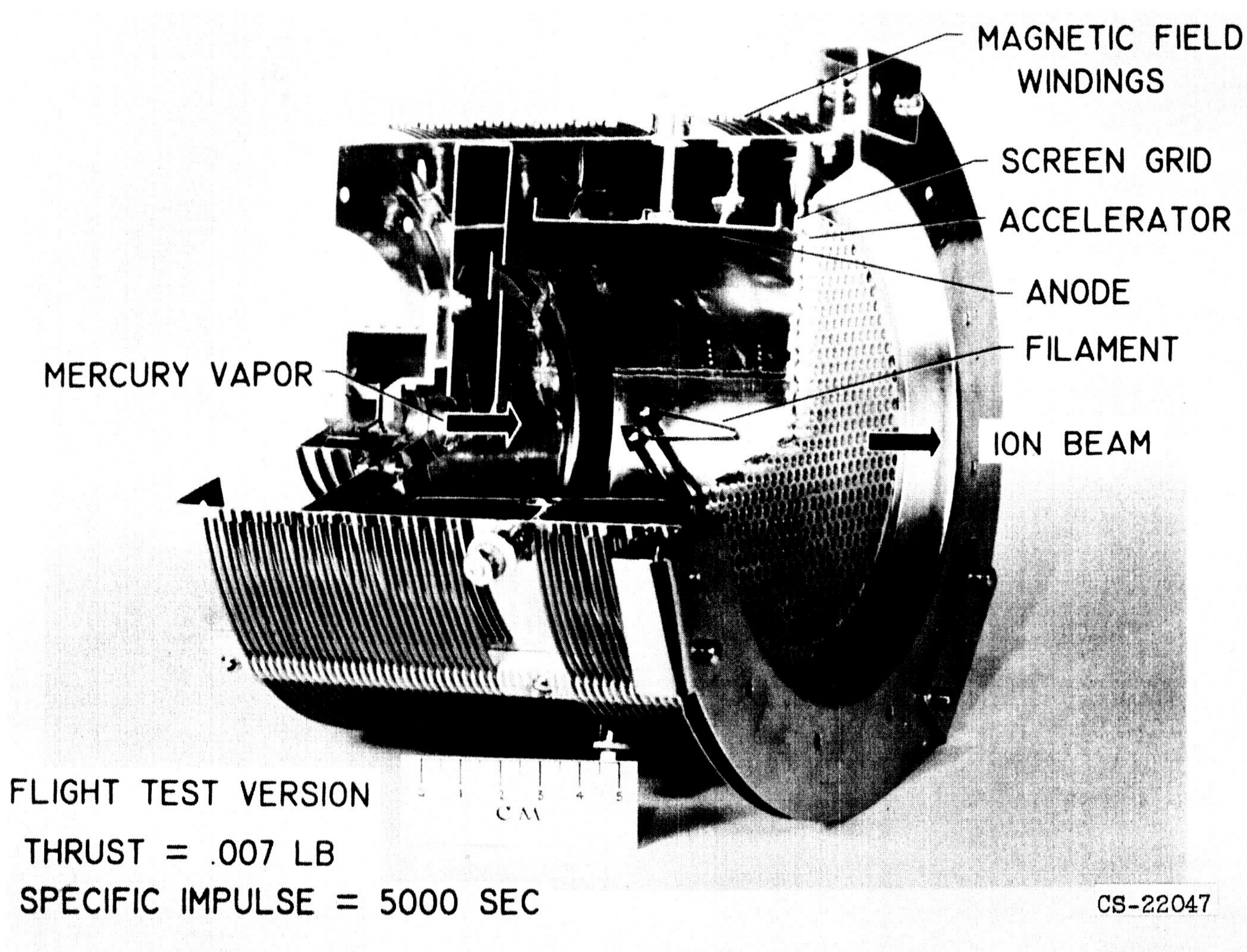

Fig. 8. - Lewis electron bombardment thrustor.

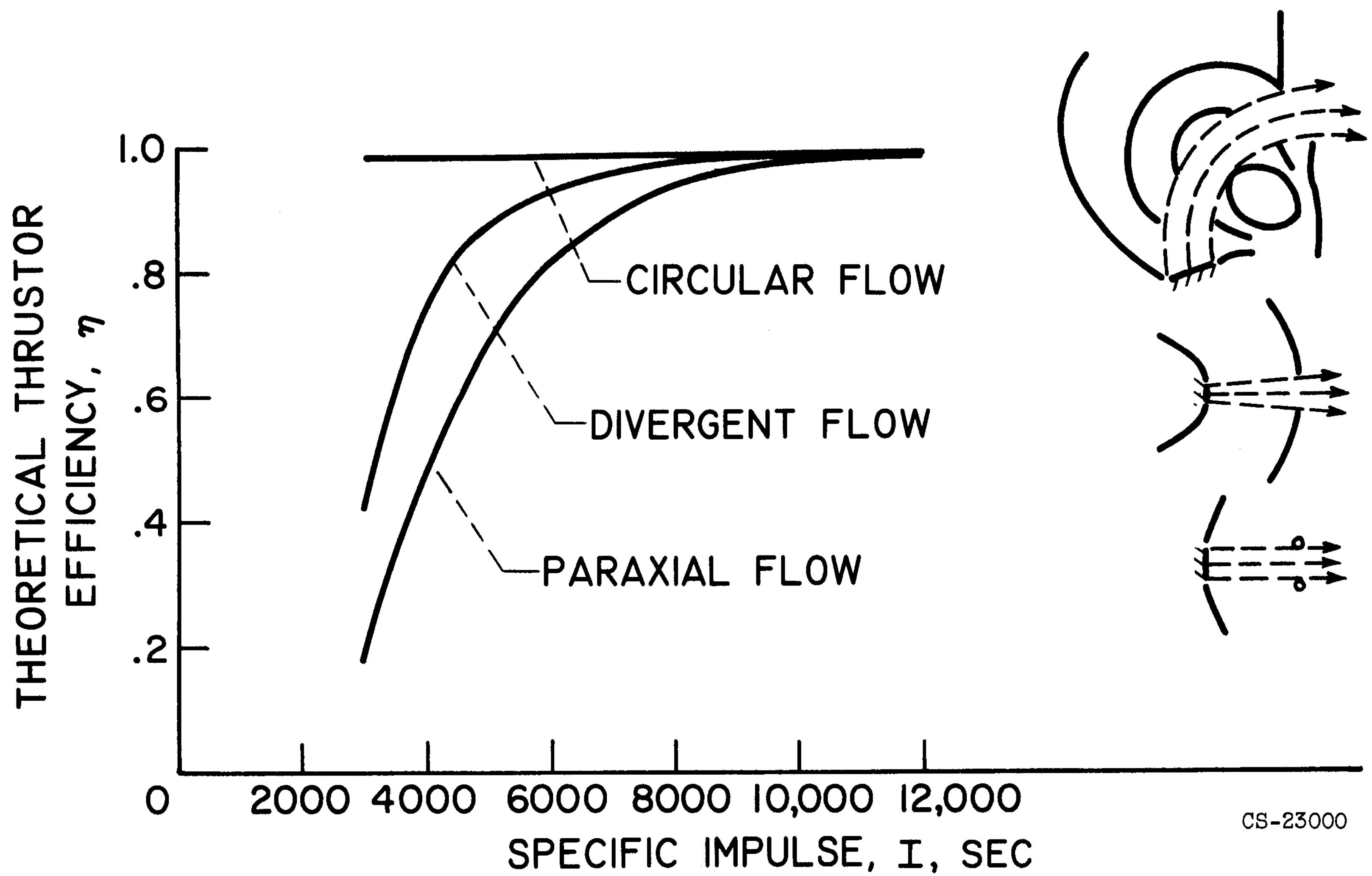

Fig. 9. - Theoretical thrustor efficiency of cesium-tungsten contact-ionization thrustors.

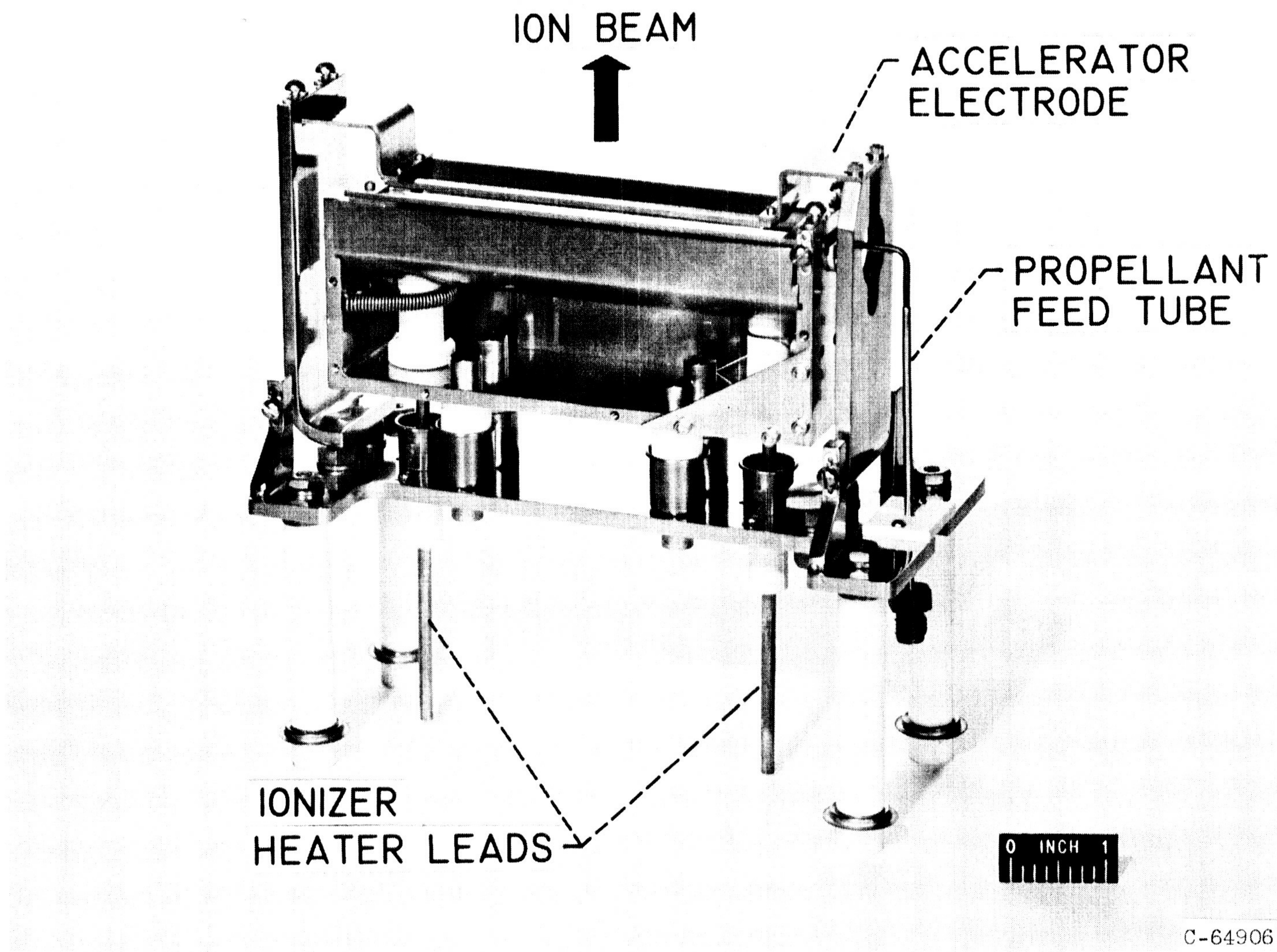

Fig. 10. - Lewis divergent flow thrustor.

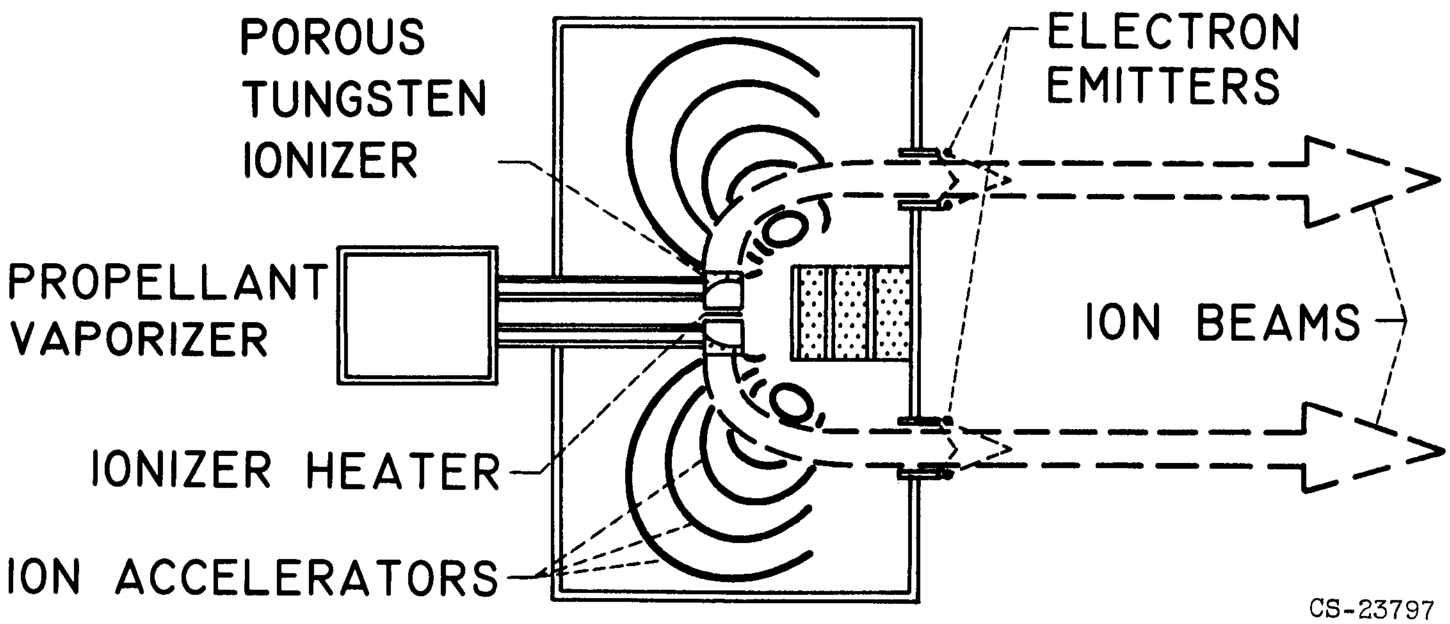

Fig. 11. - Dual beam circular flow thrustor.

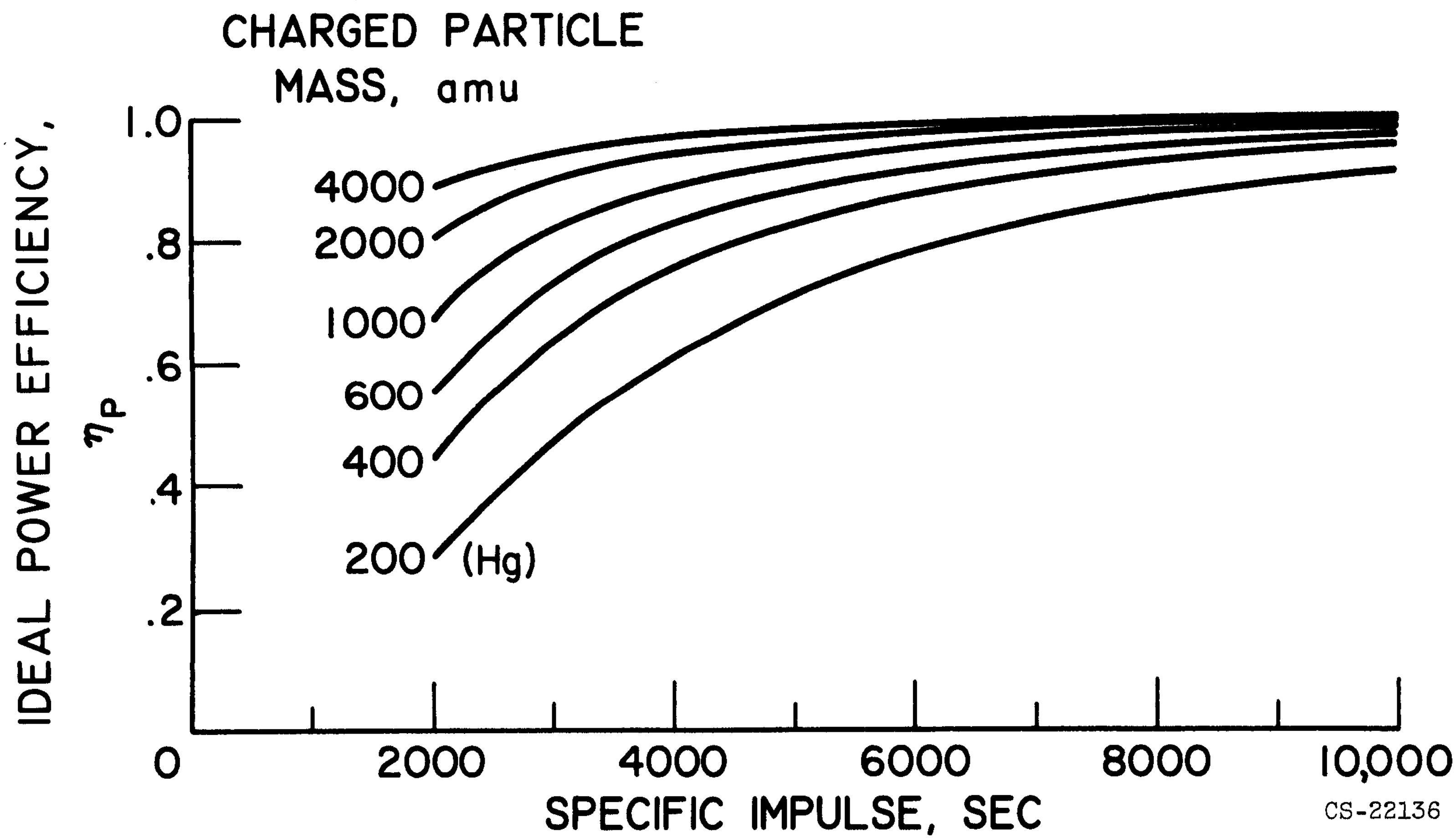

Fig. 12. - Theoretical power efficiency of electron-bombardment thrustors with heavy molecule propellants and a loss of 1000 ev/ion.

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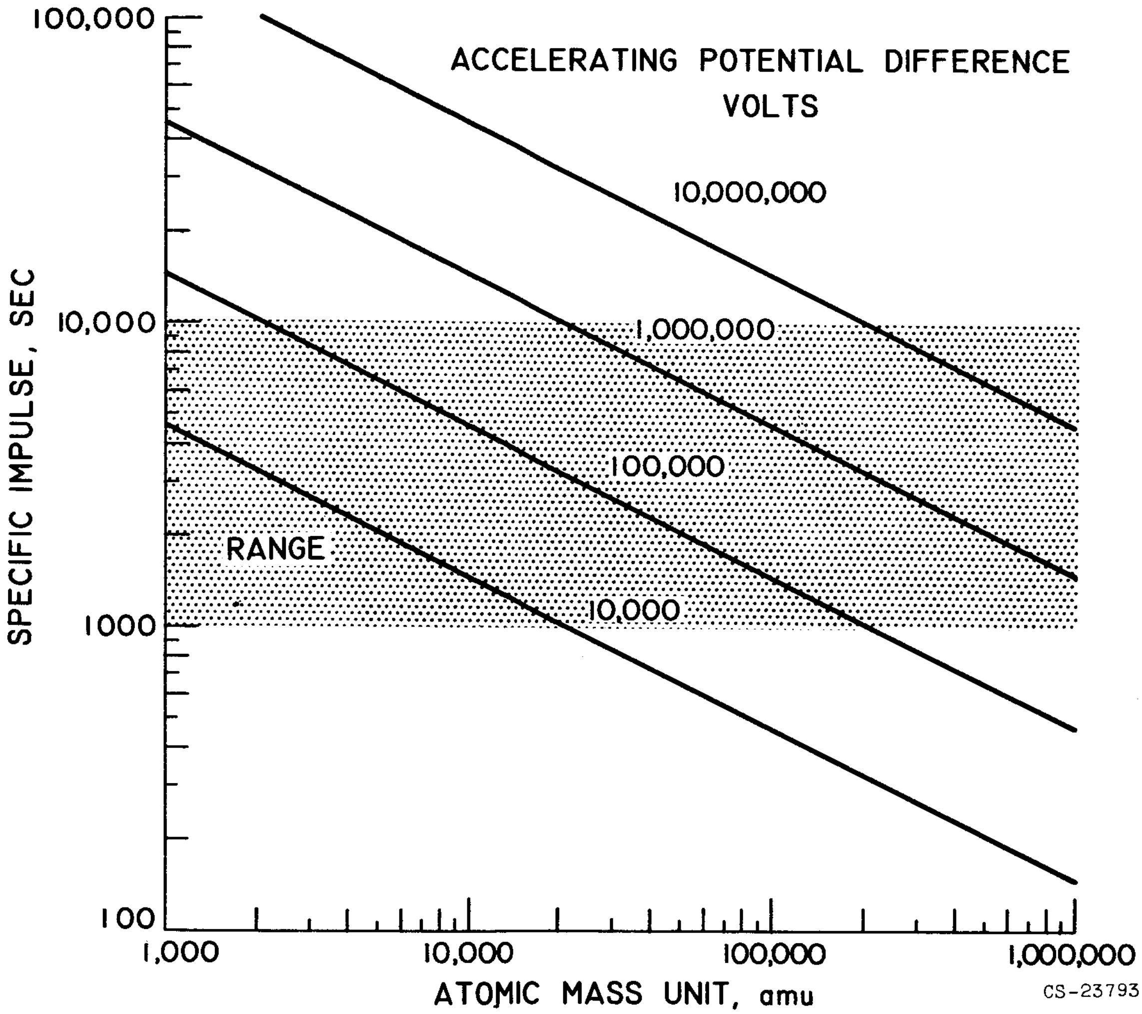

Fig. 13. - Specific impulse for a given atomic mass unit.

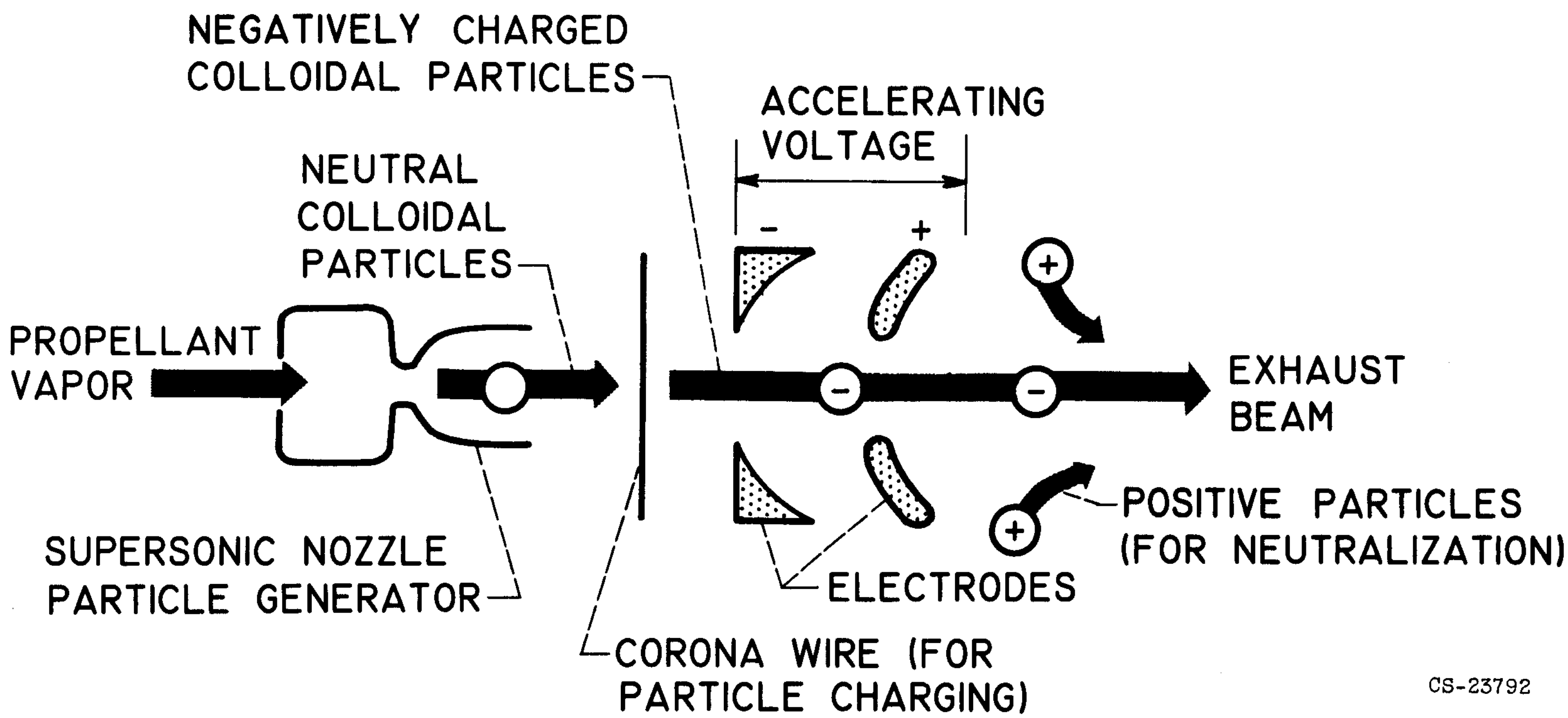

Fig. 14. - Colloidal particle thrustor.

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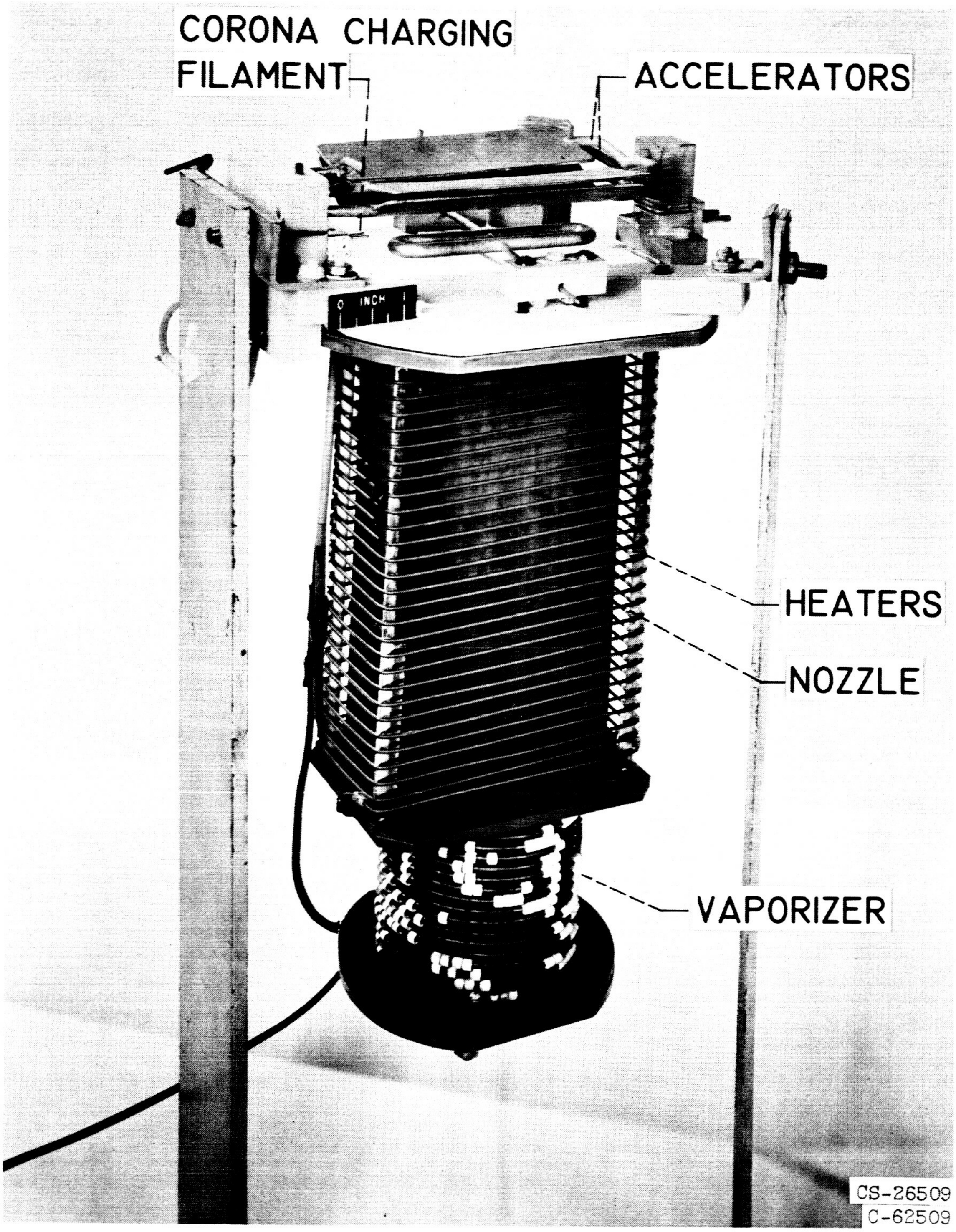

Fig. 15. - Experimental colloidal-particle thrustor with corona-discharge charging.

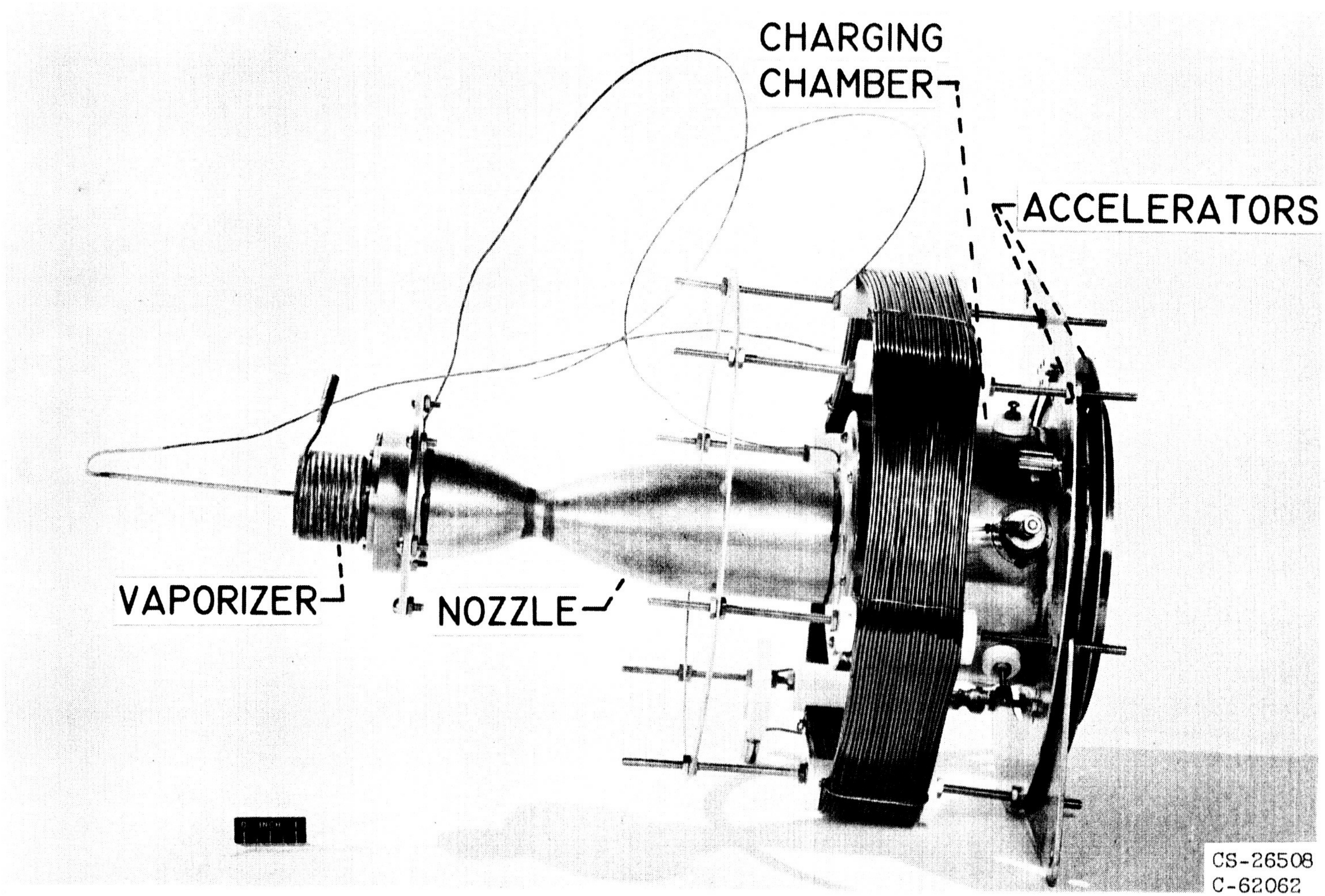

Fig. 16. - Experimental colloidal-particle thrustor with electron-bombardment charging chamber.

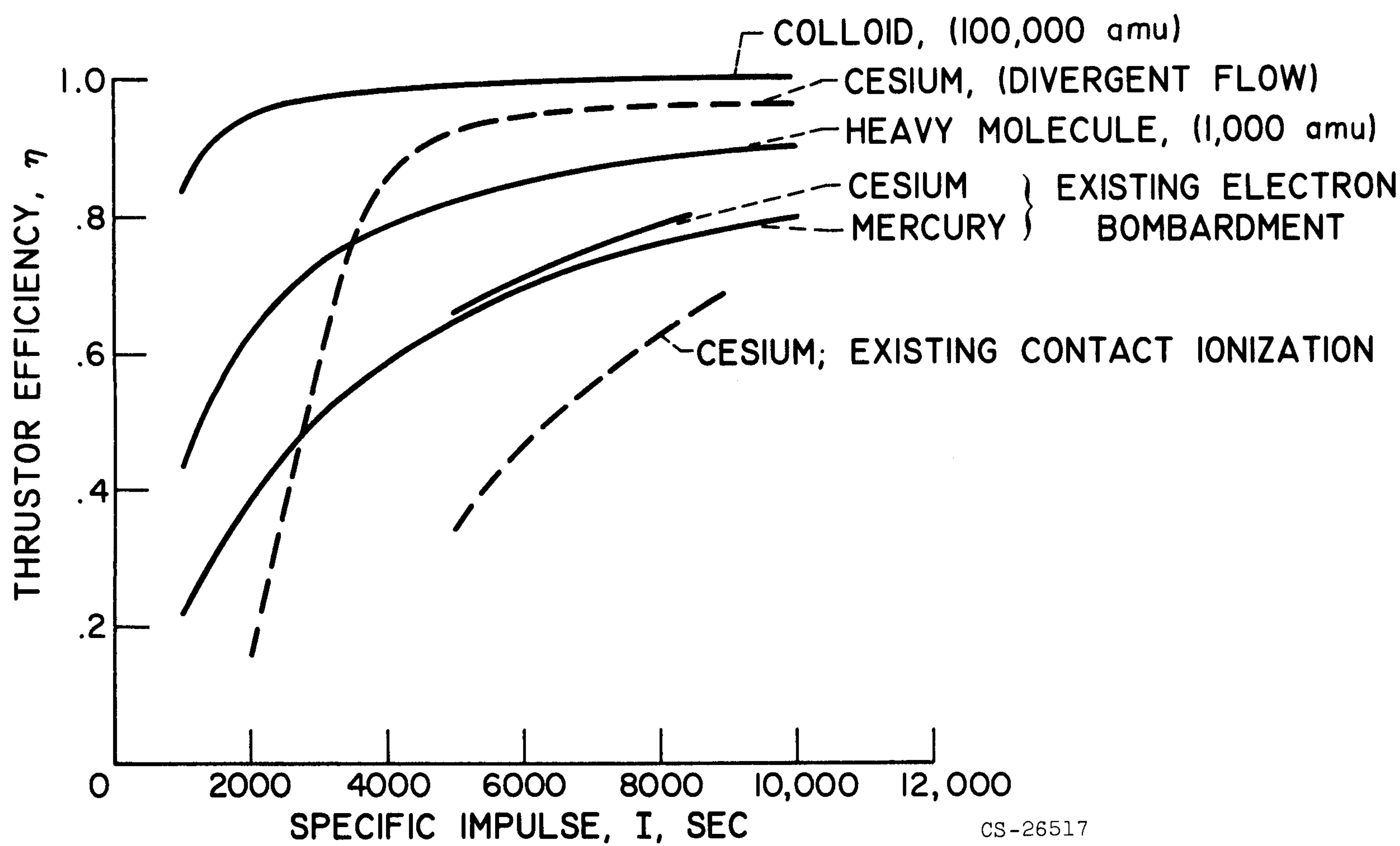

Fig. 17. - Electrostatic thrustor efficiencies.

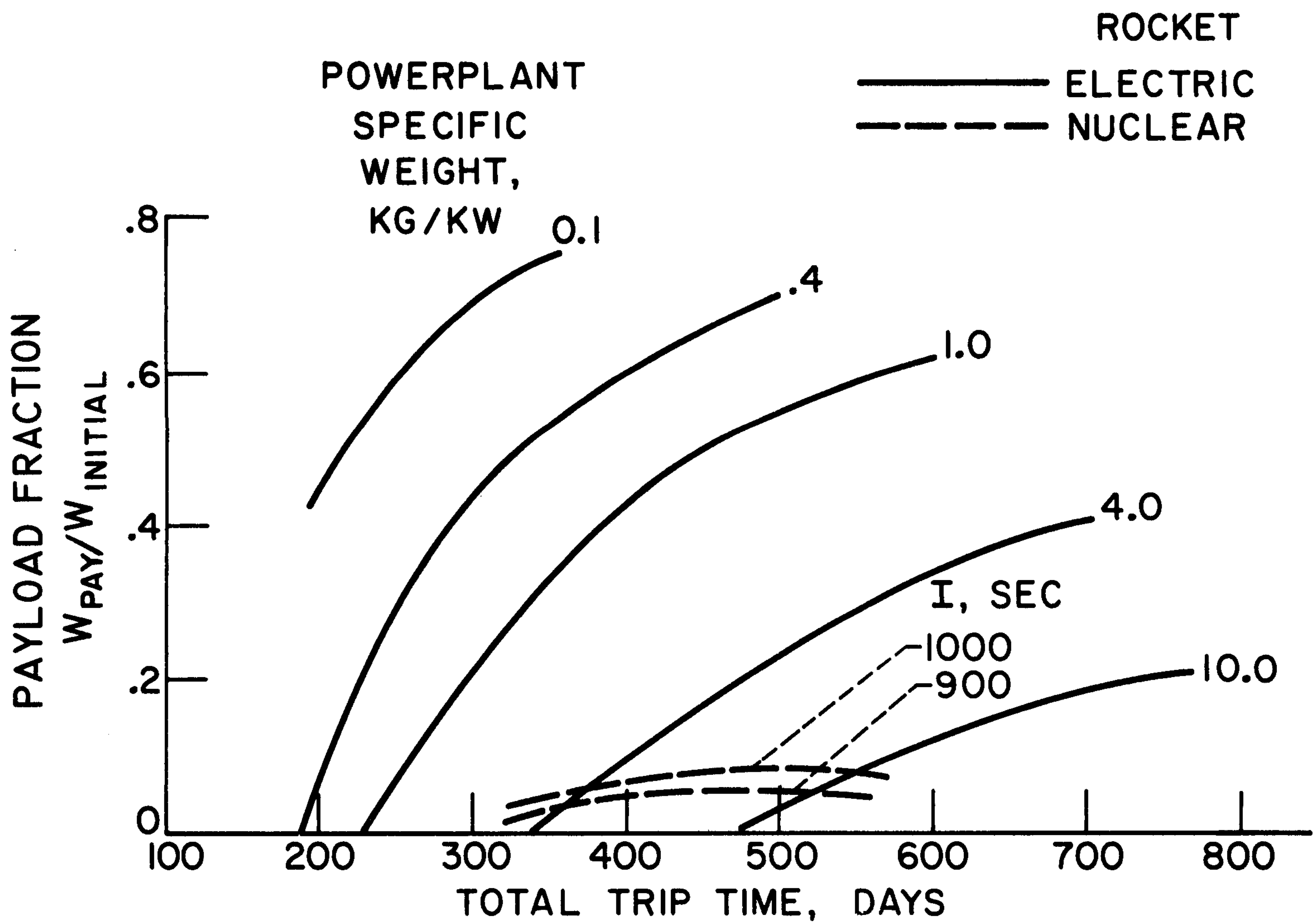

Fig. 18. - Payload fraction for Mars round trip; 25 days in Mars low orbit.

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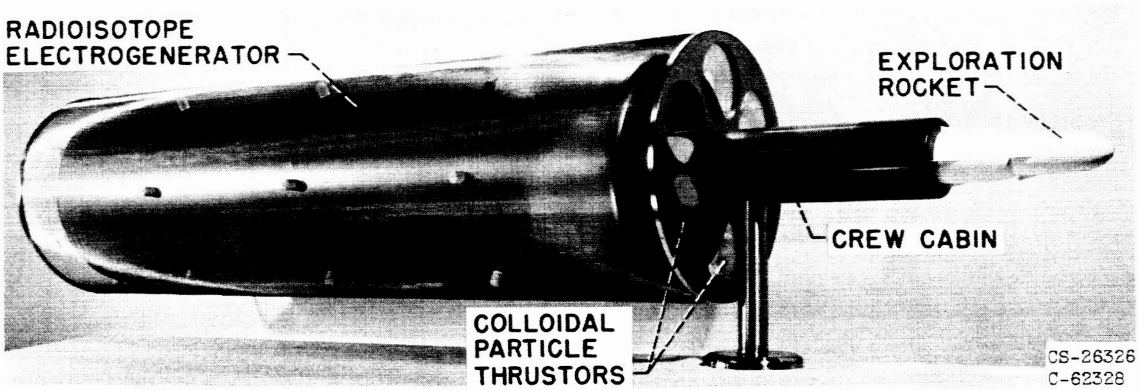

Fig. 19. - Mock-up of manned electric spacecraft.

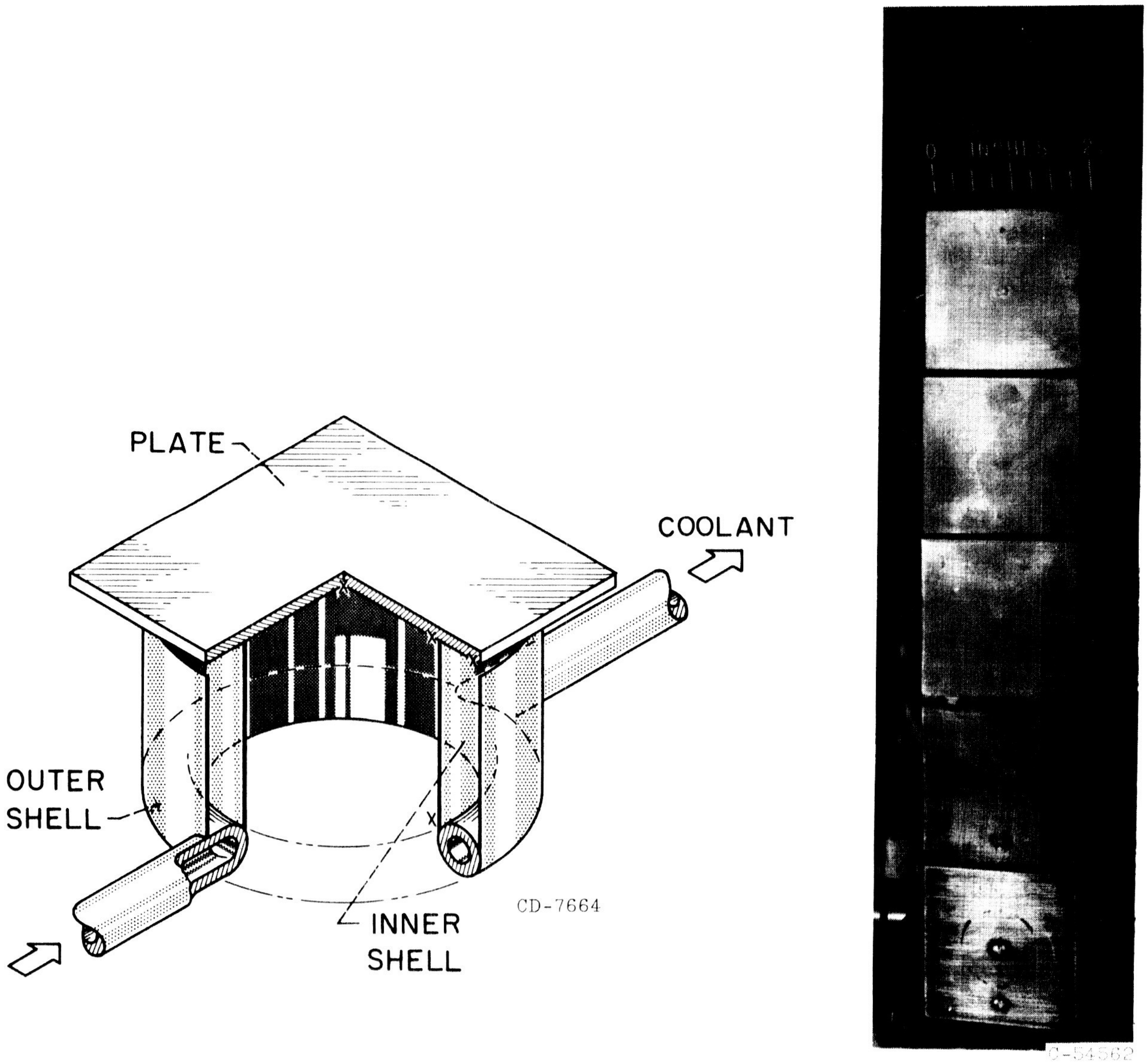

Fig. 20. - Can calorimeter.

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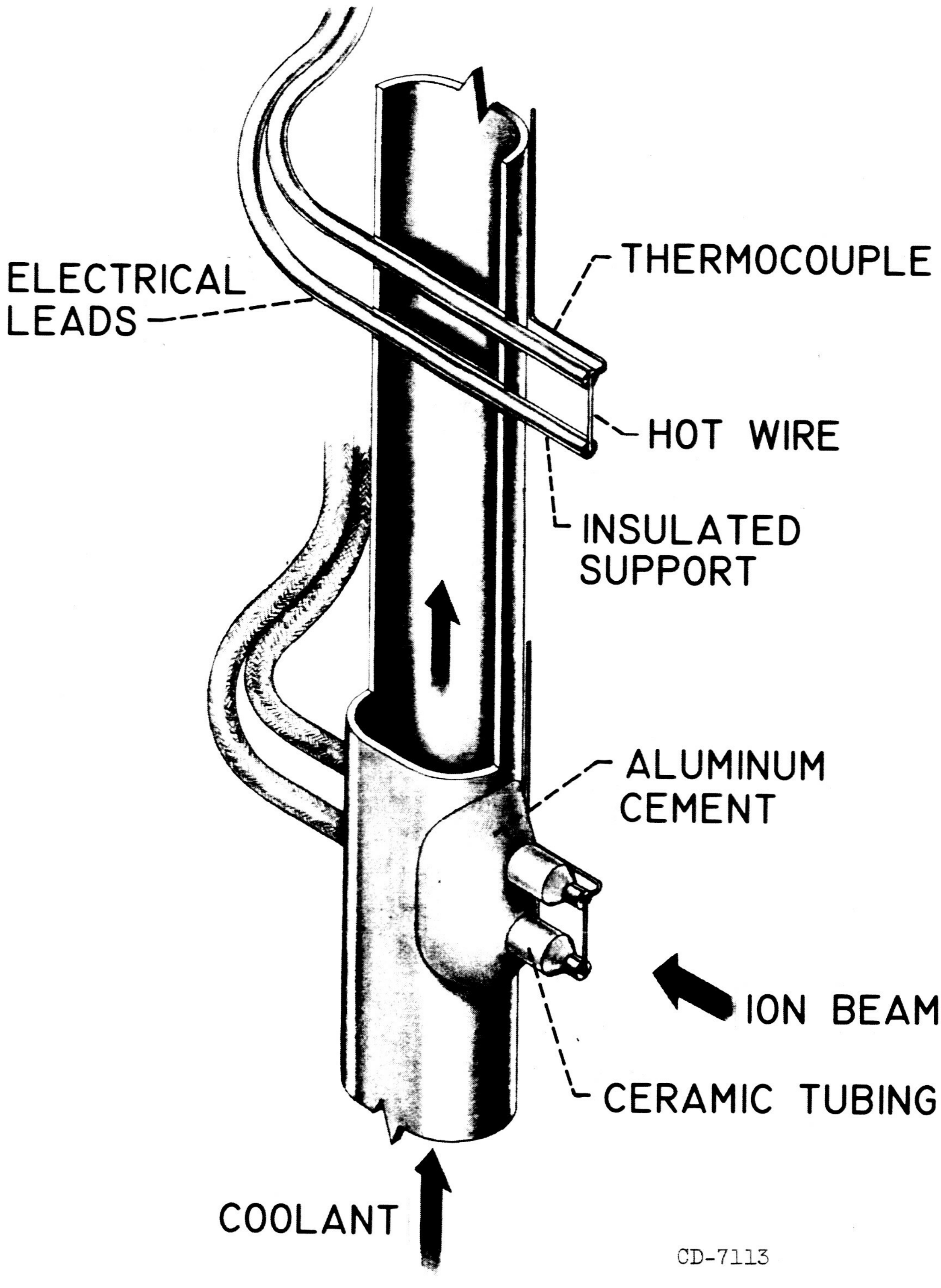


Fig. 21. - Hot-wire probe.

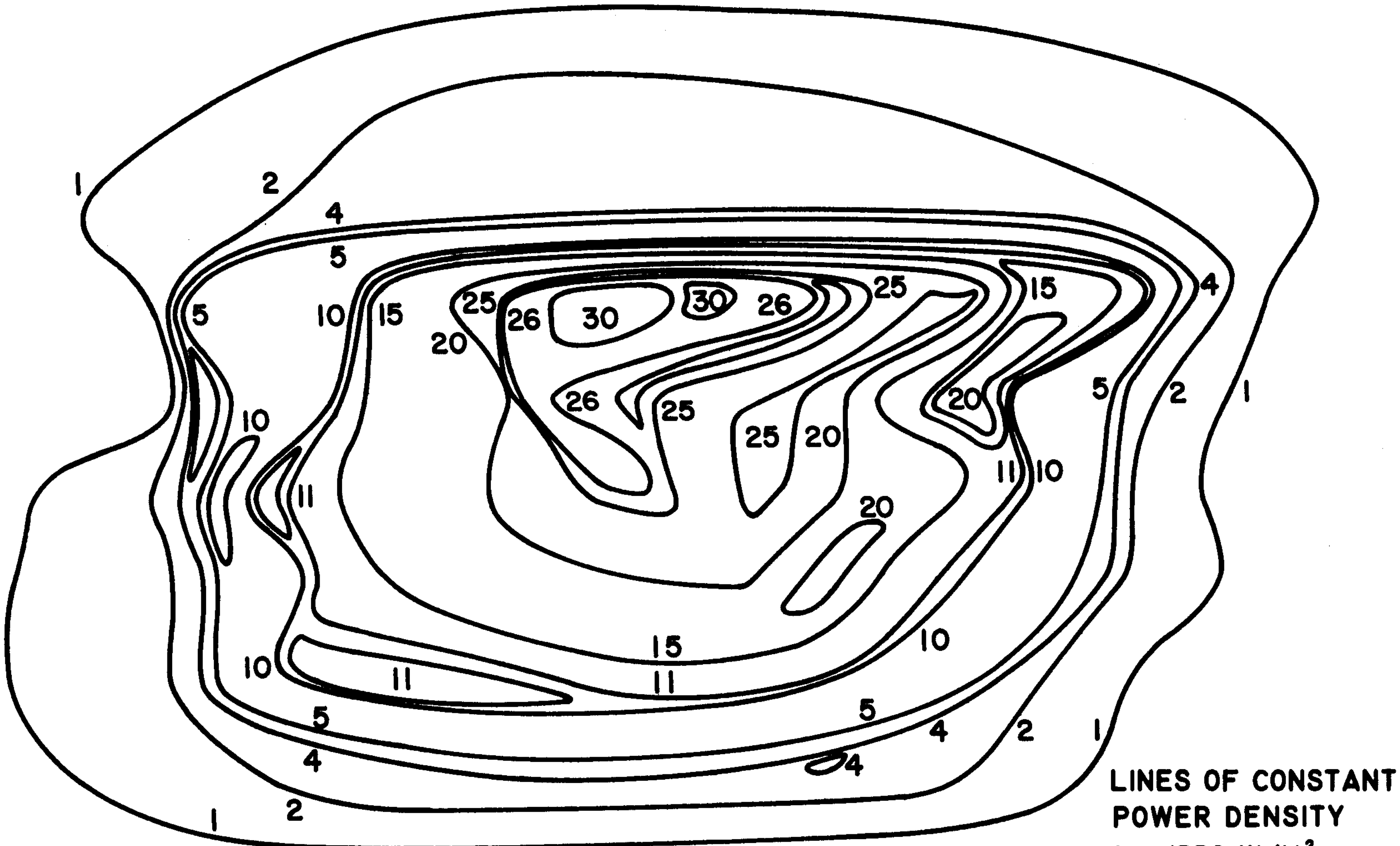


Fig. 22. - Typical ion-beam contour map. Integrated power, 908 watts; metered power, 1080 watts.

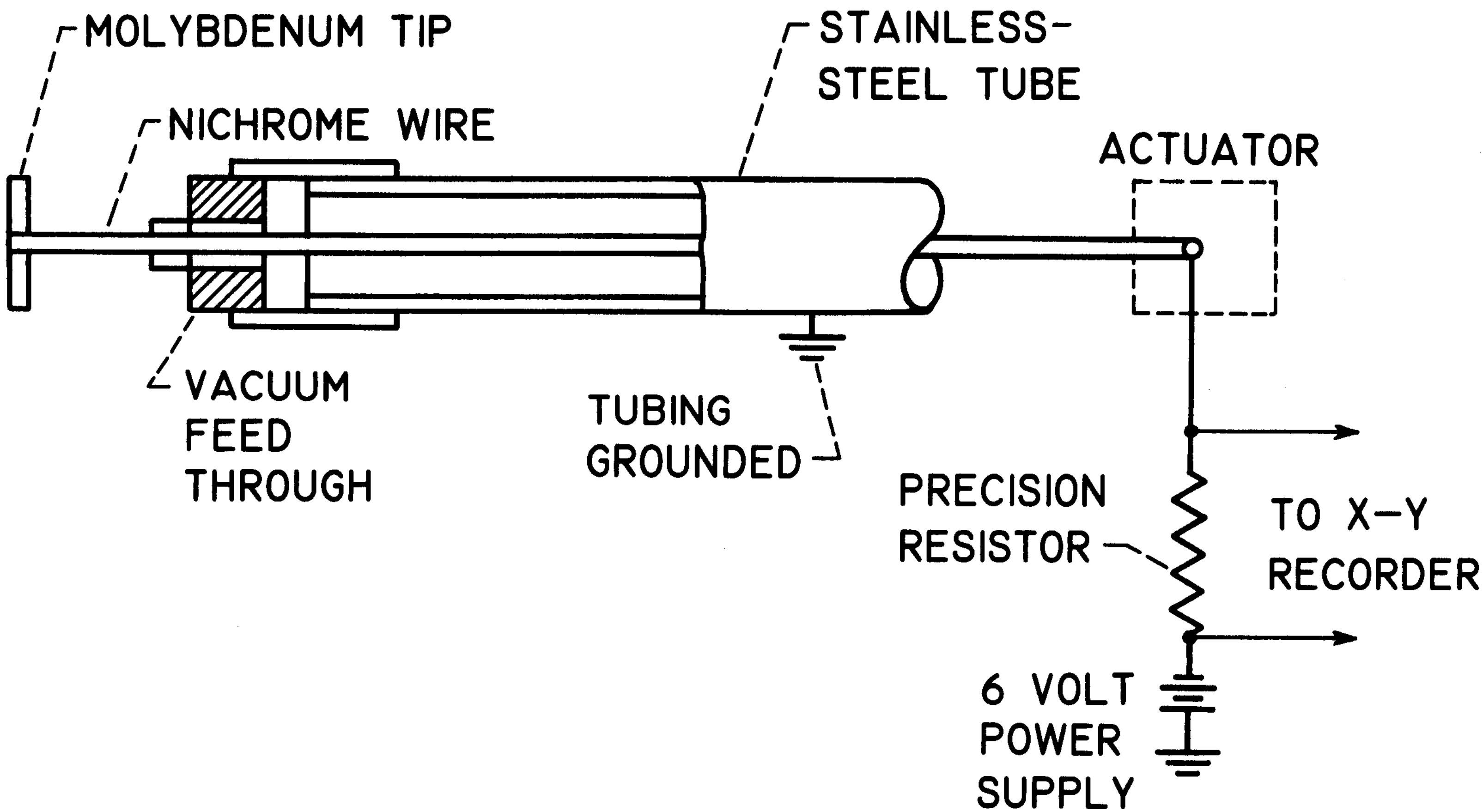


Fig. 23. - Schematic drawing of molybdenum button probe.

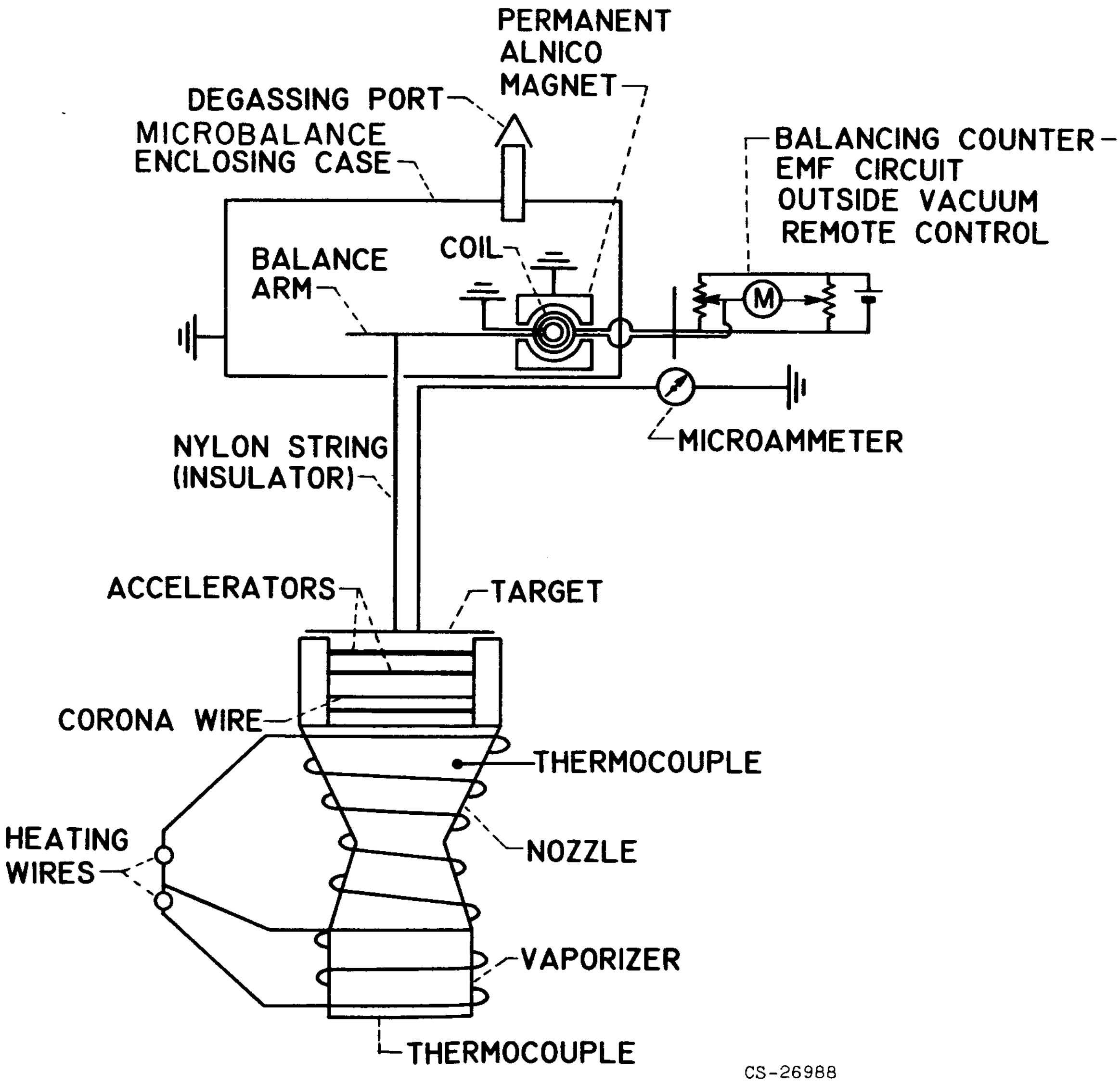


Fig. 24. - Experimental thrust-monitoring setup for colloidal particle thrustor.

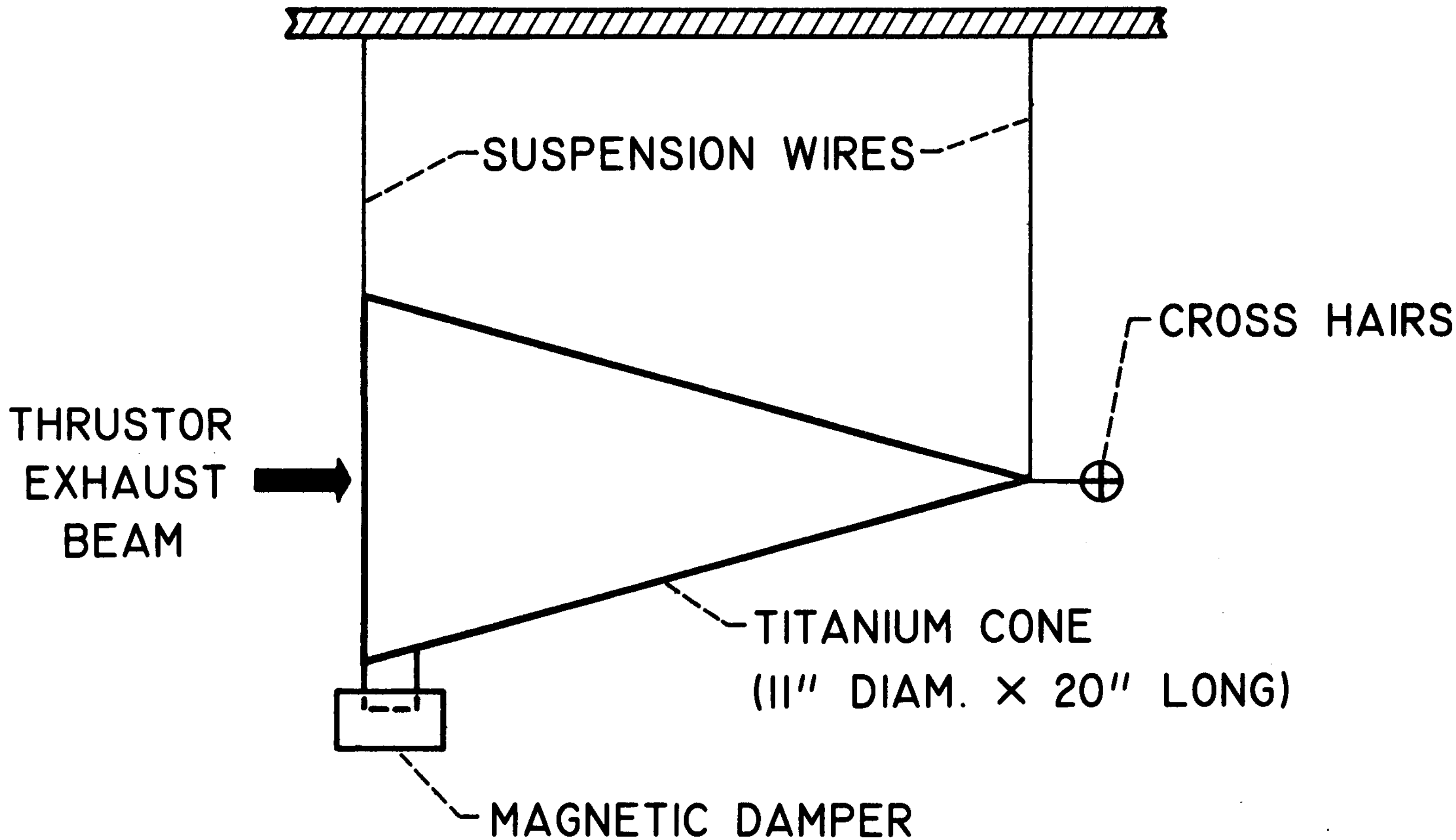


Fig. 25. - Experimental thrust target.

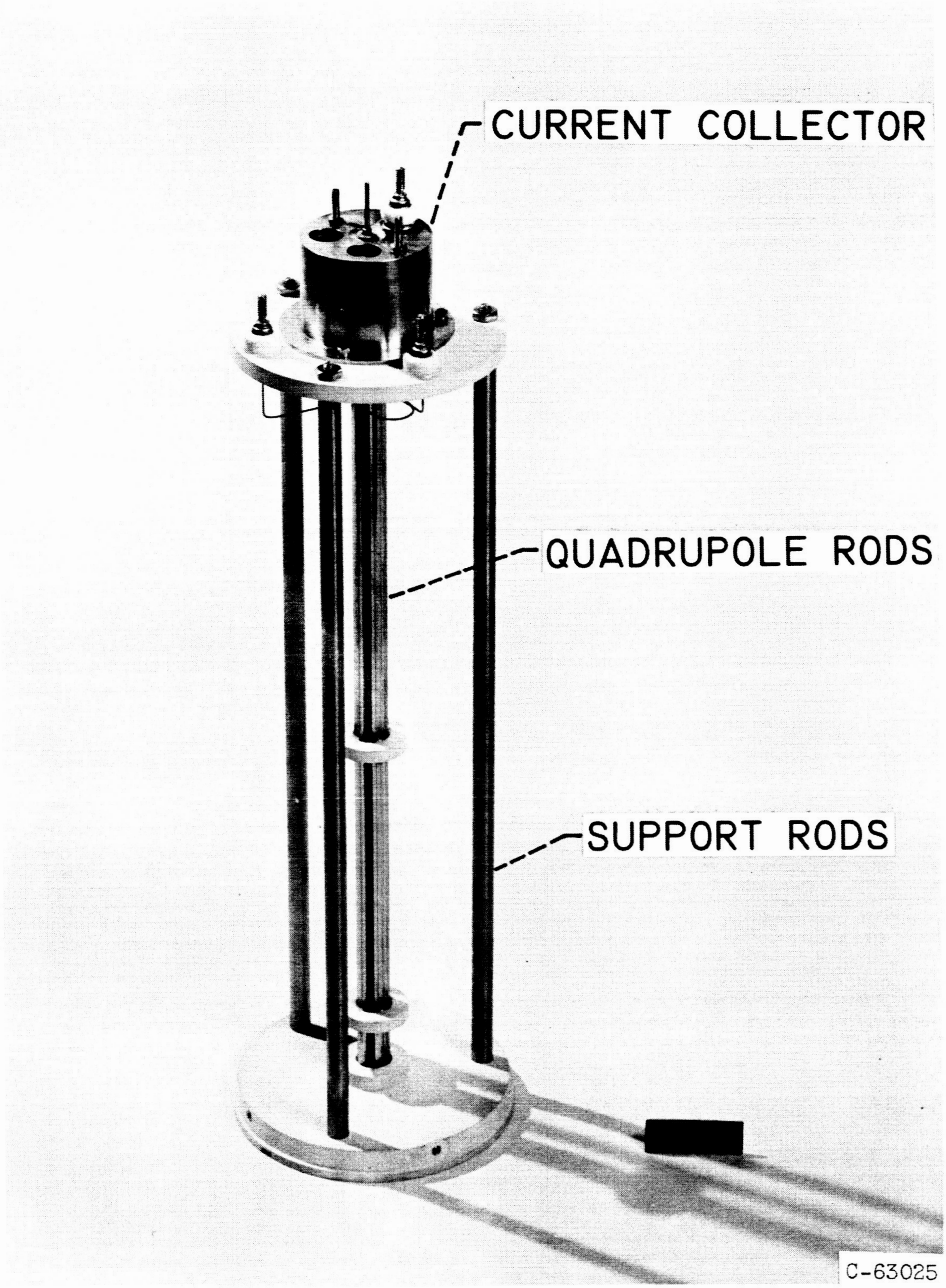
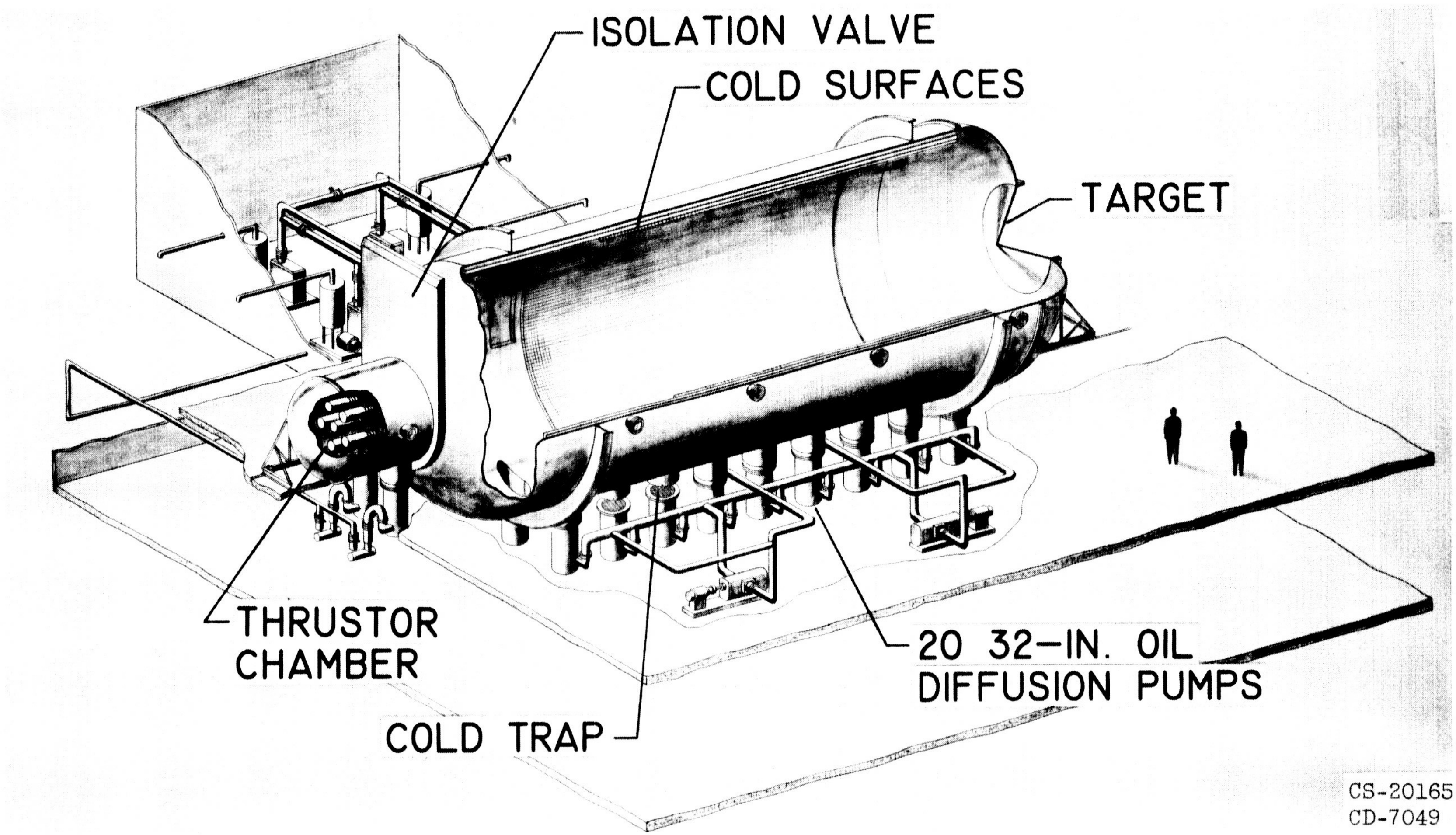


Fig. 26. Quadruple mass spectrometer.



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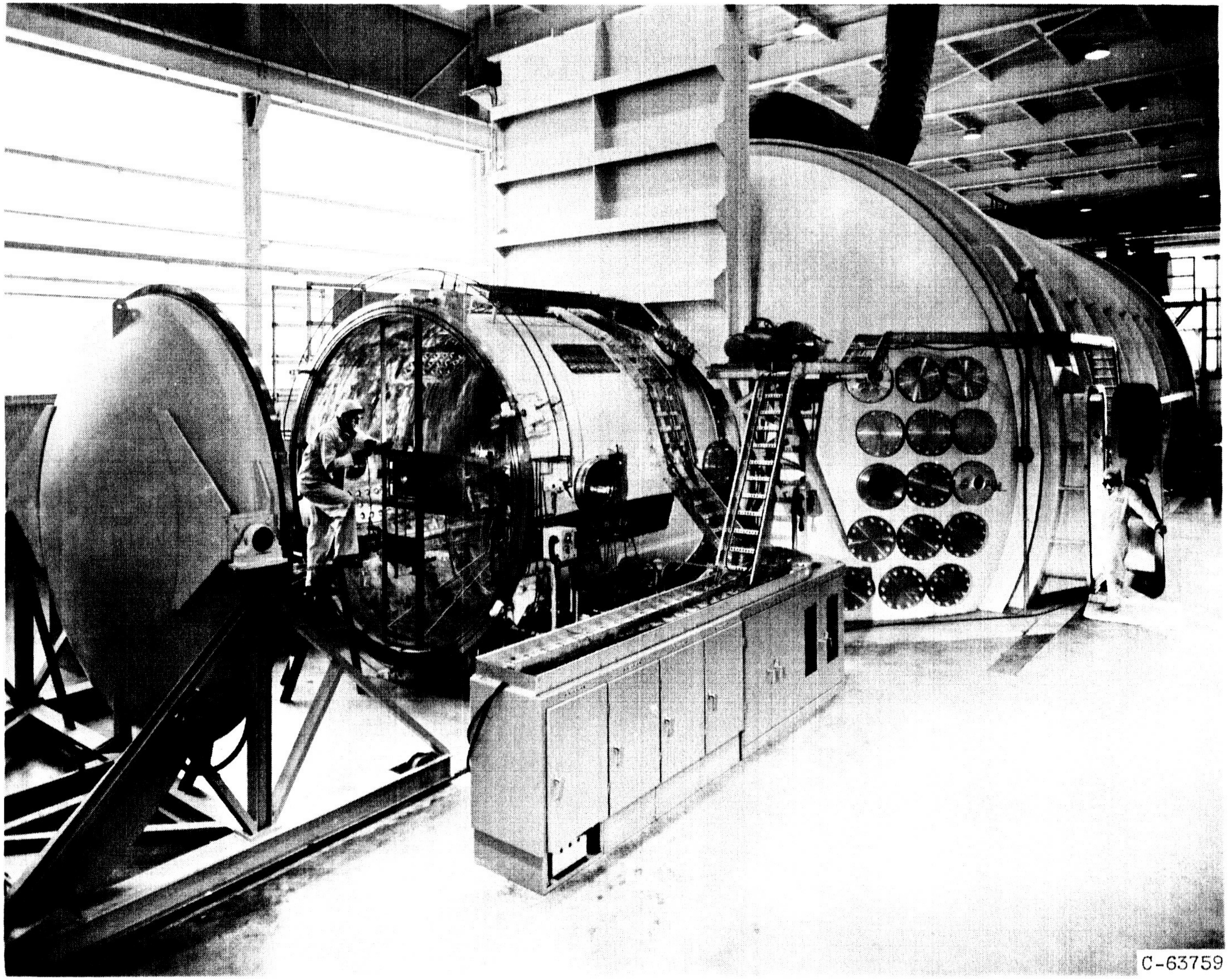
CD-7049

Fig. 27. - Electric propulsion research facility for condensable propellant electric rockets.



C-63759

Fig. 28. - Thrustor chamber of large facility.

C-62950

Fig. 29. - Interior of main chamber of large facility.